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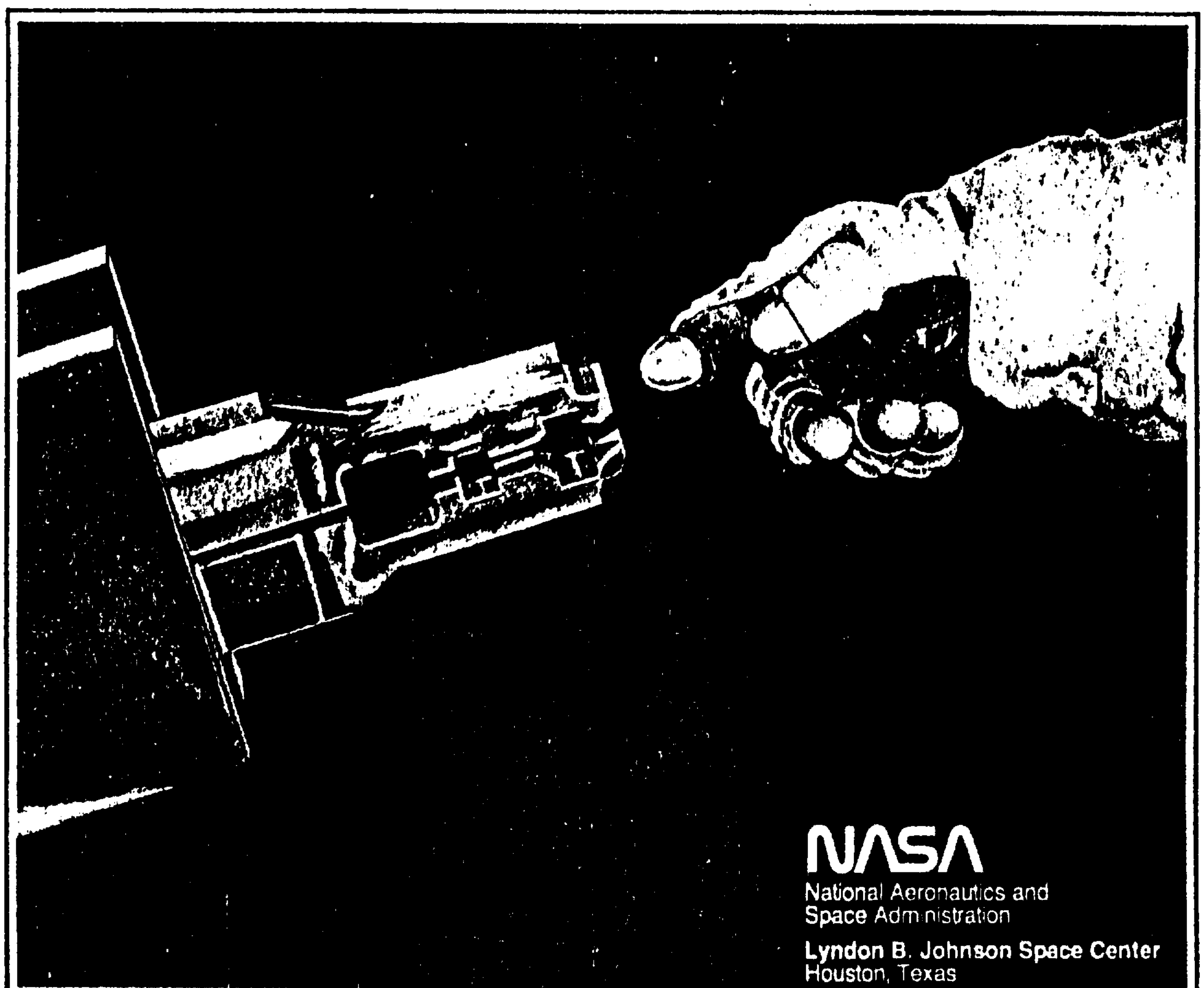
Space Station Freedom External Maintenance Task Team

Final Report

July 1990

Dr. William F. Fisher Charles R. Price



Volume I, Part 2 [redacted]

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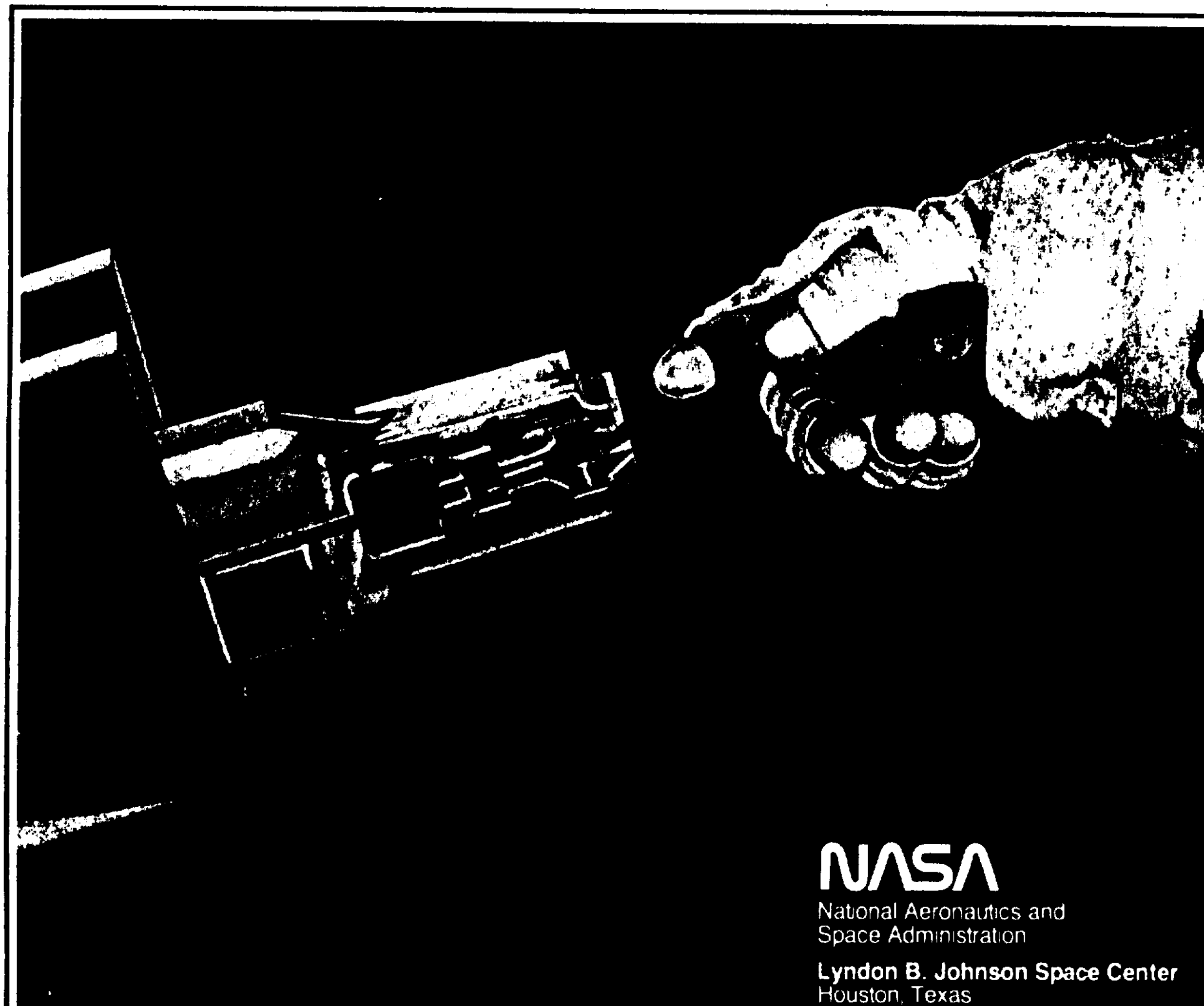

Volume I, Part 2 [redacted]

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External Maintenance Task Team

Final Report

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Preface

In late 1989, a study was performed to determine the expected amount of maintenance required for the exterior of Space Station Freedom. In this assessment, the external maintenance requirements were expressed in the hours necessary for this maintenance to be accomplished entirely by space-suited astronauts performing extravehicular activity (EVA). The results of this study indicated that the external maintenance requirements greatly exceeded the amount of EVA time that had been planned.

Although Space Station Freedom Program plans had long included the use of robots to perform external maintenance, this study did not address the amount of external activity that could be accomplished by robots.

To evaluate the maintenance requirements in greater detail and to quantify both the performance of the EVA astronauts and the Space Station Freedom robots in conducting this maintenance, a six-month study was commissioned in January 1990. The External Maintenance Task Team was co-chaired by Dr. William F. Fisher and Charles R. Price of the Johnson Space Center and was composed of official representatives identified from all relevant Space Station Program organizational elements and appropriate technical disciplines.

The External Maintenance Task Team examined the emerging Space Station Freedom design details across the 10 major Space Station Program components, assembled the information gathered into the first comprehensive database describing the nature of Freedom's design from a maintenance perspective, tested and simulated the EVA astronauts and Space Station robots performing specific maintenance tasks, and compiled a list of recommendations.

The External Maintenance Task Team found that because of the size of Space Station Freedom and the extensive number of parts comprising it, a correspondingly large amount of maintenance will be required to replace and repair failed components. The associated amount of effort necessary to maintain Freedom will also be sizable, but not insurmountable. Appropriate development and use of EVA astronauts and the Space Station Freedom robots can meet the external maintenance requirements expected by the time the Space Station is completely assembled and operational.

The task team found, however, that a significant amount of maintenance is required during the assembly of Freedom from 1995 to 1999 and that further detailed analysis must be brought immediately to bear on how to perform this activity. Furthermore, the team found that a considerable amount of spares will be required on orbit for replacement of failed components. These will be required both during the assembly phase and after assembly is complete.

The report that follows presents the comprehensive results of the efforts of the External Maintenance Task Team. Volume I provides an overview of the task team's approach and includes detailed discussion of the findings and recommendations that resulted. Volume II describes the database and contains much of the actual data currently available.

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Acronyms and Abbreviations

AC	Assembly Complete
AL	Air Lock
AOA	Assembly Operation Assessment
APS	Astronaut Positioning System
ASPS	Attachment Stabilization and Positioning System
BIT	Built-in Test
CCTV	Closed Circuit Television
CDR	Critical Design Review
CEI	Contract End Item
CETA	Crew and Equipment Translation Aid
CG	Center of Gravity
CIL	Critical Items List
CM	Center of Mass
CMG	Control Moment Gyro
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CSA	Canadian Space Agency
D&C	Display and Controls
DCD	Design Criteria Document
DM	Dexterous Manipulator
DMS	Data Management System
DOF	Degree of Freedom
DTC	Design-to-Cost
DTF	Development/Demonstration Test Flight
EE	End Effector
EMTT	External Maintenance Task Team
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
EVAS	EVA System
EVR	Extra Vehicular Robotic
EV	Extravehicular
FEL	First Element Launch
FMEA	Failure Modes and Effects Analysis
FP	Fisher-Price
FTS	Flight Telerobotic Servicer

g	Gravity
GE	General Electric
GFE	Government Furnished Equipment
GPC	General Purpose Computer
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ICD	Interface Control Document
IEA	Integrated Equipment Assembly
IP	International Partner
IR	Infrared
ITA	Integrated Test Area
IVA	Intravehicular Activity
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
JSC	Lyndon B. Johnson Space Center
KSC	John F. Kennedy Space Center
LERC	Lewis Research Center/NASA
LCC	Life Cycle Cost
LDEF	Long Duration Exposure Facility
LEE	Latching End Effector
LeRC	Lewis Research Center
MAGIK	Manipulator Analysis - Graphic, Interactive, Kinematic
MBS	MRS Base System
MDSSC-SSD	McDonnell Douglas Space Systems Company - Space Station Division
MIL-STD	Military Standard
MLI	Multilayer Insulation
MMD	Micrometeroid Debris
MPAC	Multipurpose Application Console
MPTT	Multipurpose Torque Tool
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Center
MSIS	Robotic Systems Integration Standard
MSS	Mobile Servicing System
MT	Mobile Transporter
MTBF	Mean Time Between Failure
MTBMA	Mean Time Between Maintenance Actions
MTBP	Mean Time Between Penetration
MTTR	Mean Time to Replace
ORU	Orbital Replacement Unit
OSE	Ocean Systems Engineering, Inc.

PDGF	Power Data Grapple Fixture
PDR	Preliminary Design Review
PDP	Programmable Display Pushbutton
PERT/CPM	Program Evaluation Review Technique/Critical Path Method
PFR	Portable Foot Restraint
PNP	Probability of No Penetration
POR	Point of Resolution
PRACA	Problem Reporting and Corrective Action
PRLA	Payload Retention Latch Assembly
PWP	Portable Work Platform
PWS	Portable Workstation
QD	Quick Disconnect
RADC	Rome Air Development Center
RMS	Remote Manipulator System
RPS	RMS Planning System
RSEL	Robotic Systems Evaluation Laboratory
RSIS	Robotic Systems Integration Standard
RTAIL	OSE's Robotics Testing and Integration Laboratory
SAE	Storage Accommodation Equipment
SAIC	Science Applications International Corp.
SPAR	SPAR Aerospace Ltd.
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SSF	Space Station Freedom
SSRMS	Space Station Remote Manipulator System
STD	Standard
TBD	To Be Determined
TR	Telerobot
ULC	Unpressurized Logistics Carrier
UPT	User-Provided Tool
WAF	Work Site Attachment Fitting
WETF	Weightless Environmental Test Facility
WP	Work Package

Executive Summary

Executive Summary

Background

In October 1989, a team headed by Dr. C. Bryant Cramer was directed by NASA to provide an estimate of the amount of extravehicular activity (EVA) that would be required to maintain Space Station Freedom. Their findings were that for the completely assembled station, approximately 432 hours of extravehicular repair time would be required at the worksite per year of operation. When maintenance uncertainties and the overhead associated with EVA were considered, the Cramer group concluded that a total of 1732 hours of EVA would be required on an annual basis to maintain the Space Station. This was the equivalent of 2.8 two-man EVAs per week.

At that time, the NASA allocation for EVA external maintenance was only 132 total hours per year, or approximately one 2-man EVA per month. To resolve the apparent discrepancy between the Cramer study estimate and the NASA allocation, an External Maintenance Task Team (EMTT) was formed by NASA in December 1989.

Co-chaired by Dr. William F. Fisher, astronaut, and Mr. Charles R. Price, Chief of the Robotics Systems Development Branch at the NASA-Johnson Space Center (JSC), this group was given the authority to review all aspects of Space Station Freedom external maintenance and repair. They were directed to define these maintenance requirements, and make any appropriate recommendations for decreasing them, by July 1, 1990.

Methods

The Space Station Freedom is a large and complex system, still in its design phase. To avoid the problem of having to re-evaluate the overall impact of every small change as it occurred, the EMTT found it necessary to freeze the Space Station design in order to analyze it. Thus, with the exception of some of the data on failure rates, this report represents a snapshot in time of Space Station Freedom as it existed between January and March 1990.

The EMTT divided its activities into two parts. First, there was an initial data gathering phase, in which an inventory of information was compiled from all Space Station Freedom work packages, contractors, and international partners. Secondly, there was an extensive analysis of this data, the final product of which is represented by the text of this report.

Counting the Replacement Items

In the initial phase, the members of this team began a count and identification of all the individual items that would require EVA maintenance or replacement (Orbital Replacement Units or ORUs). While each work package, NASA contractor and international partner had records of how many of these items it had, the sum of these numbers for the Space Station was not known. The EMTT obtained all available records on these ORUs, including failure rates, repair times, duty cycle, quantity of a given type, etc., directly from the work packages. Once identified, these parameters were then placed into a single database, the text of which is included in Volume II of this report. This database allows for the analysis of multiple ORU characteristics, and through software updating can easily be kept current as future changes in ORU design or requirements occur.

Failure Rates of Components

In addition to their number, the rate at which these ORUs would be expected to fail is a critical determinant of the external maintenance requirement. After closely reviewing all the information on the ORU failure rates provided by the Space Station Freedom Program, the EMTT found that the methods for estimating these failure rates differed somewhat from one NASA program element to another. To standardize the method of calculating failure rates, and to bring the overall failure rate picture into sharper focus, members of the EMTT felt that expertise from outside NASA was required.

To accomplish this purpose, the services of the Science Applications International Corporation (SAIC) were utilized to make an independent evaluation of the failure rates for all the external ORUs on Space Station Freedom. Their findings were subjected to an internal SAIC audit, and finally reviewed by a blue ribbon panel. This panel was chaired by former astronaut and Senator Harrison Schmitt, and comprised individuals expert in the fields of reliability, component failure rates, and statistical analysis. Both the SAIC report, its appendices, and the blue ribbon panel review of that report have subsequently become part of this document (see Appendix A).

Because of the limitations of time and resources, the SAIC study did not include estimates for the EVA maintenance requirements of the Scientific Payloads ("Users") Community. These were provided by the NASA Space Station Program Office (Level II), and have decreased sharply from their original estimates made during the initial EMTT data gathering phase. Also, for a variety of reasons, the SAIC could not fully address all the failure rates for ORUs within the European Space Agency (ESA) and the planned crew return vehicle. These estimates were obtained separately by members of the EMTT, and have been added to the SAIC estimates in obtaining the final external maintenance requirements.

EVA Worksite (ORU Replacement) Times

Two other factors which are essential in the estimate of the overall external maintenance requirements are the time necessary to replace an ORU once it has failed and the overhead associated with getting the EVA crew member to the worksite.

The EMTT began the evaluation of ORU replacement ("worksite") times by looking at the data provided by the Space Station Program elements across NASA. Significant differences were noted in the way this time was calculated, however, with some estimates including overhead and uncertainty values and others being based on repair times in "shirt sleeves" rather than in a pressurized spacesuit. No two NASA program elements used the same method in calculating ORU worksite times.

In an effort to standardize this process, the EMTT developed an unambiguous definition of the worksite time for future estimates (see Appendix C). Using this definition, the estimates were scrubbed of overhead and other material that did not fall into the worksite time category.

In addition to standardizing the definition of worksite time, it was the intention of team members to refine the ORU worksite time estimates. This was to be done by performing a step-by-step analysis of the tasks based on the detailed ORU engineering drawings. This task would have been performed by a single group experienced in EVA timeline development, in much the same manner as the EVA overhead analysis discussed below. Close examination of the ORU designs, however, has shown the vast majority of them to be too immature to permit any of the detailed analysis necessary for accurate timeline development. Consequently, EMTT members have elected to accept the "scrubbed" (i.e., overhead and K-Factor removed) worksite times provided by the individual work packages and have included these estimates in the analysis of external maintenance requirements. A much more detailed study of the actual ORU replacement times at the worksite will be necessary once ORU designs are finalized.

EVA Overhead

The overhead associated with getting the EVA crew member to and from the worksite with tools and spare ORUs was also closely analyzed. The original estimate by the Cramer study was admittedly an approximation. It intentionally did not include some known overhead activities and determined this value at 1.7. This can be interpreted as meaning that a task requiring one hour at the worksite would require an additional 0.7 hours of overhead in getting everything ready to start work. In estimating the total EVA requirements, the EVA overhead was factored in by multiplying the total worksite time by 1.7.

Using the expertise of the Mission Operations Directorate at NASA-JSC, a detailed analysis of the actual EVA overhead factor for Space Station Freedom was performed as a part of the EMTT study. This necessitated a good understanding of Space Station architecture, as well as requiring experience in the field of EVA timeline and procedures development. Through this method, it was determined that the actual EVA overhead was **at least** 6.0. This states that five hours of overhead is required to perform a single one-hour ORU replacement task, and was significantly higher than predicted in any previous estimates.

Two important assumptions were made in this overhead analysis that must be taken into account if the value of 6.0 is to be viewed in its proper perspective. One is the assumption that all tasks are equal to or less than the average worksite time of 1.1 hours (actually, 25% take longer). The other is that each worksite task requires only a single EVA crew member (in fact 25% of the tasks require two). Time and resources did not permit these additional analyses, but they would clearly have increased the overhead value of 6.0 significantly. Thus, the overhead value of 6.0 represents a conservative number for the current Space Station design.

The results of the overhead study were then compared with actual EVA flight experience on the Space Shuttle and on Skylab. In addition, engineering evaluations of selected aspects of Space Station overhead activities were performed by space-suited astronauts in the weightless environment training facility at NASA JSC. In each case, a very close correlation was observed between the EMTT EVA overhead estimates of 6.0, previous flight experience, and the engineering test runs.

K-Factor

In any repair activity, false alarms, component damage, and component malfunctions are possible. When large numbers of different repair tasks are performed on complex systems, it can be assumed that such unplanned events will occur. The result is an increased workload which is referred to as the K-Factor, and it is defined as the ratio of maintenance actions to actual hardware failures.

Most estimates from the aerospace and other industries have placed the value of this K-Factor at about 2.0, as did the Cramer study. The EMTT performed its own evaluation of what K-Factor should be for systems on Space Station Freedom.

This evaluation was accomplished by breaking the Space Station ORUs into six different categories (see Appendix D) and developing different K-Factors for each. The K-Factors for the individual categories vary from 1.51 to 3.11, with an effective average of 2.03. The text of this analysis and its rationale are contained in Appendix D of this report.

Preventive Maintenance and Inspection

Two additional aspects of the external maintenance requirements addressed by the EMTT are preventive maintenance and inspection. Both were felt to be important, with inspection allowing early failure detection of some components, and preventive maintenance allowing repair tasks to be anticipated and grouped for increased EVA efficiency. The importance of these activities has a strong operational rationale, with significant portions of the overall maintenance budget of nuclear power plants, naval vessels, aircraft, etc., being dedicated to them. For example, 70% of the maintenance on a typical nuclear submarine is classed as "preventive" in nature.

The EMTT studied these issues, and has concluded that there is currently no NASA plan for such activity on Space Station Freedom.

It is the consensus of EMTT members that most of the inspection requirements (once they are identified) can be performed by the use of cameras and robotics within the current design of Space Station Freedom. While preventive maintenance was investigated by EMTT members, its importance is largely dependent upon the maintenance philosophy to be adopted by the Space Station Program. Much of the impact of these two areas on external maintenance will have to await the development of such an overall maintenance strategy.

The Role of Robotics

The use of robotics to reduce the EVA maintenance requirements is currently part of the design baseline for Space Station Freedom, but the EMTT study represented the first detailed evaluation of robots participating in maintenance activities. It also became the first analysis of robotic efficiency wherein all the different Space Station robots were evaluated as a team. This consisted of detailed discussions of Space Station robotic capabilities, sophisticated robotic computer simulations and physical tests in the JSC robotics laboratories.

The EMTT performed multiple task analyses of robots supporting external maintenance in two different modes. The first assumed the robot served the function of supporting the EVA tasks in the pre-EVA worksite set-up activities and during the performance of an actual EVA. The second mode considered robotic performance of an entire repair task independent of EVA crew members. In both cases, the robots were assumed to be operated by the crew from inside the pressurized volume of the Space Station as per the current design.

In each scenario, it became clear that ORU design to maximize compatibility for robotic repair was critical to the success of robotics on the Space Station. It was also found that ORUs can be designed for both robotic and EVA compatibility. An evaluation of various ORU designs among the work package elements revealed that while some significant ORU-to-robot design compatibility has been achieved by some work packages, a great amount of effort remains to be done.

With the current Space Station Freedom baseline design, an operational analysis revealed that the crew time required to perform ORU replacements using the robots was equal to or less than the crew time required to perform the same kinds of tasks by EVA. Estimation of the benefits of adding more automatic features to the current robot designs revealed that dramatic decreases in the crew time required to perform maintenance could be realized.

EVA Requirements to Support Scientific Research

Numerous scientific payloads are baselined on Space Station Freedom, and will require EVA or robotic installation and removal. Estimates prior to this study were approximately 150 hours of worksite time per year, and estimates initially provided to the EMTT by the Space Station Program Office were 73 hours of worksite time annually. These estimates by NASA have come down even further recently, with values of 50, 15, 30 and most recently 22.5 hours of required worksite time. The Space Station Program Office has also stated that there is no plan to repair any payload malfunctions on orbit, and subsequently have not included such activity in their revised estimates of required EVA time.

Members of the EMTT have made their own general estimates of what these requirements will be, but there is much uncertainty in this area. For the purposes of calculating the overall external maintenance requirements, the NASA estimate of 22.5 hours per year was used.

There is also some concern among EMTT members that the stated NASA policy of not making any on-orbit repairs on scientific payloads is unrealistic, and a reconsideration of this policy could significantly increase the EVA external maintenance requirements.

Results

The findings of the External Maintenance Task Team are reported below. They represent a detailed and thorough estimate of the external maintenance requirements for Space Station Freedom as it existed in the first quarter of calendar year 1990. Extensive documentation for each aspect of these results can be found in the text and appendices of this report.

Most of the values below were obtained by combining the failure rate data analysis for Space Station Freedom compiled by SAIC with the NASA estimates for baselined external scientific experiments ("Users") and the EMTT estimates for ESA, and the crew return vehicle.

Number of external ORUs	8,158
Different types of external ORUs	~450
Average EVA maintenance actions per year	507
Peak maintenance actions per year	1004
Low maintenance actions per year	353
Average ORU replacement time (hrs.)	1.1
Average K-Factor	2.03
EVA overhead	6.00
Inspection overhead	Undetermined
Preventive maintenance overhead	Undetermined

The demand expression for calculating the overall maintenance requirements is as follows:

Total External Maintenance Time

Expected Maintenance Time =

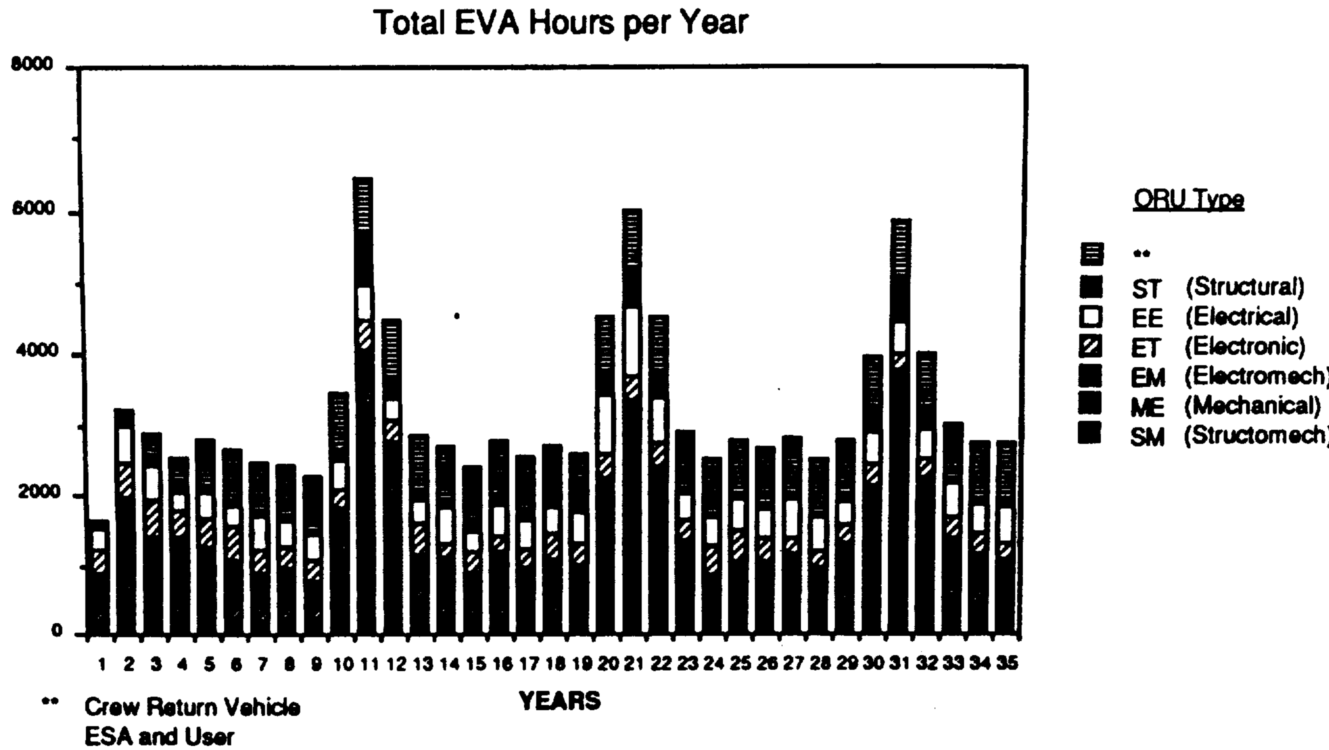
$$\sum_{1}^{6} \left(\begin{array}{c}\textbf{Generic No. of}\\ \textbf{Failures/Class}\end{array}\right) \left(\textbf{K-Factor}\right) \left(\begin{array}{c}\textbf{Expected}\\ \textbf{Replacement}\\ \textbf{Time}\end{array}\right)$$

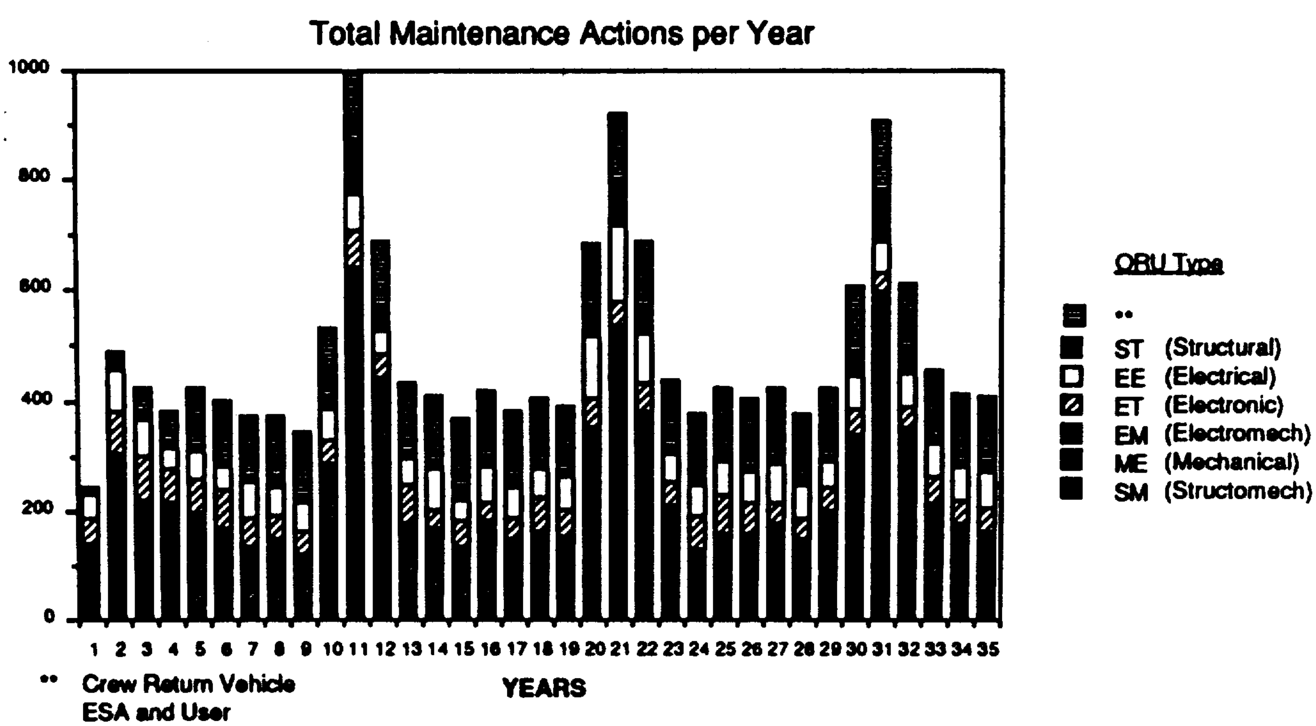
Estimated by "Monte Carlo" simulation Includes effects of • # ORUs • Failure Rate • Duty Cycle	Estimated by Contractors + JSC and has the form $K = K_1 + K_2 + K_3 + K_4 + 1$	• MTTR estimated by contractors • EVA overhead estimated by JSC

X000890M

It is the opinion of the EMTT that the external maintenance requirements for Space Station Freedom as they existed in the first quarter of 1990 are as presented in graphic and tabular form below. These data do not include any allowances for preventive maintenance, inspection activities, or discount for robotic performance of maintenance.

Space Station Freedom
External Maintenance Demand Summary





Note: Year 1 = First Element Launch + 12 Months

SSF External Maintenance Demand Summary

Average External Maintenance Requirements Over 35 Years

- 507 maintenance actions per year
- 625 EVA worksite hours per year
- 3,276 total EVA time required per year
- 273 two-man EVAs per year
- 5.3 two-man EVAs per week

External Maintenance Requirements From First Element Launch To Permanent Manned Presence (First 30 Months)

- 941 maintenance actions
- 6,267 total EVA time required
- 522 two-man EVAs total
- 4.0 two-man EVAs per week

External Maintenance Requirements From Permanent Manned Presence To Assembly Completion (24 Months)

- 811 maintenance actions
- 5,250 total EVA time required
- 437 two-man EVAs total
- 4.2 two-man EVAs per week

Total External Maintenance Requirements From First Element Launch To Assembly Completion (Total 54 Months)

- 1,752 maintenance actions
- 11,517 total EVA time required
- 960 total two-man EVAs
- 4.1 two-man EVAs per week

Total External Maintenance Requirements During Peak Demand Year (2005)

- 1004 maintenance actions
- 6462 total EVA time required
- 538 total two-man EVAs
- 10.4 two-man EVAs per week

Total External Maintenance Requirements During Low Demand Year (2003)

- 353 maintenance actions
- 2,272 total EVA time required
- 189 total two-man EVAs
- 3.7 two-man EVAs per week

Observations and Discussion of Results

In addition to identifying the external maintenance requirements for Space Station Freedom, the EMTT has spent extensive time and resources identifying ways to decrease them. In addition, other issues have been identified which, while not directly related to decreasing maintenance requirements, will need to be addressed prior to beginning station construction. This report contains 95 such recommendations for improving efficiency and decreasing maintenance requirements, and these recommendations are tabulated under a separate section. Observations on those recommendations that the EMTT believes to be the most significant are discussed below.

Maintenance Requirements Prior To Assembly Completion

An estimated 1,752 maintenance actions requiring on-orbit replacement will occur prior to the completion of Space Station Freedom. The independent failure rate analysis by SAIC predicts that approximately 941 of these are expected to occur prior to a permanent manned presence. There is currently little reserve in the assembly manifest to accommodate ORU replacements prior to the permanently manned capability phase.

While the time from the man-tended phase to assembly completion allows for some EVA repair activity, the SAIC data can be used to predict that an additional 811 EVA maintenance actions will be required. If only a small subset of these failed ORUs are replaced prior to assembly completion, an unacceptable backlog of maintenance tasks will have developed before full operations have begun.

Another consideration is that an ORU replacement requires that the spare ORU be available. A logistics plan must be developed within the Space Station Program that would make such a large number of required spare ORUs available on orbit.

It is of the greatest importance that the Space Station Freedom Program address how maintenance will be accomplished in the period prior to the completion of Space Station construction. The assembly launch manifest must be revised to allow for additional EVA repair time, and for the placement of the required spares on orbit during this period.

In addition, a general logistics plan for ORU on-orbit resupply must be developed based on the anticipated ORU failure rates for the 35-year lifetime of the Space Station. Incorporated in this plan must be a strategy for determining which ORUs will need to be stored on the Space Station, how many will be needed, what their power and thermal requirements will be, where they will be kept, and what role will be assumed by preventive maintenance.

EVA Overhead Reduction

The EVA overhead value of 6.0 represents the single greatest change in any parameter analyzed in this report, increasing 350% over the value cited in the Cramer study. Part of this increase is based on an evaluation of all end-to-end overhead tasks, and part is due to a complete analysis of the requirements based on current Space Station architecture It is also a conservative value, since it intentionally did not take into account those 25% of tasks requiring greater than 1.1 hours or those tasks requiring two EVA crew members.

Since the overhead figure is a direct multiplier of the worksite time, any reduction in its value would have a profound effect on the overall maintenance requirements. It is the opinion of this task team that if all 20 of the EMTT recommendations for decreasing EVA overhead are implemented, its value could be reduced to approximately 2.5. This would have the effect of reducing the EVA requirements from 5.3 to 2.1 EVAs per week (averaged over 35 years), and from 10.4 to 4.2 EVAs per week (peak demand/year 2005). Although it is recognized that such changes would involve some architectural modifications and would have an impact on weight, volume, cost and the assembly manifest, the potential gains would seem to be overriding.

Another design goal throughout the Space Station Program should be to require that all ORUs be replaceable by a single EVA crew member or robot in 1 hour or less. This, when coupled with implementation of the 20 EVA overhead reduction recommendations, would have the effect of reducing the overhead factor to 2.0, as well as significantly decreasing the overall worksite time required.

The significant EVA requirements occurring prior to assembly completion will have a unique EVA overhead value, dependent upon Space Station architecture at the time and the possible use of the Space Shuttle as a base of operations. This new overhead value will need to be more fully understood in order to determine the maintenance requirements during the assembly phase.

ORU Reliability Improvements

While over 8,100 external ORUs and approximately 450 ORU types have been identified on Space Station, certain classes of ORUs have a disproportionate effect on the total maintenance requirement. Efforts should be concentrated on increasing the reliability and decreasing the numbers of these ORUs. A summation of such savings across the maintenance-intensive ORUs could significantly decrease the external maintenance requirement.

Common ORU Design

A significant number of the total ORU count represent items that could be placed into standard "boxes." Such a common design would decrease cost by decreasing redundant hardware, as well as facilitating task performance by both EVA crew members and robots. While many different designs for such boxes are being developed across the Space Station Program, no standard box design exists for Space Station ORUs.

In April 1990, EMTT team members initiated efforts to develop a standard ORU box design. Working with Ocean Systems Engineering (OSE) and all work package and international partner ORU designers, significant progress on potential design standards has been made (Appendix G). This work will serve as a nucleus for future solutions in this area.

It is the recommendation of the EMTT that the Space Station Program develop a single design standard for all ORU boxes on Space Station Freedom. This design should facilitate rapid removal and installation by an EVA crew member and be completely compatible with robotic interfaces.

The Robotic Contribution

The Space Station robots have been found to provide a worthwhile resource capable of assuming most of the external maintenance workload by assembly complete. The performance of the robots for external maintenance is enabled through robot-compatible ORU design. An 80% goal of robot-compatible ORUs is recommended, but can only be achieved through the establishment of associated design standards.

The Space Station robots should be further integrated regarding the performance of maintenance among the robots themselves. All robots should be capable of being repaired to the greatest extent possible by some combination of the other robots without the use of EVA. The design standards for robot-compatible ORUs should be applied to the robots' ORUs.

With the current Space Station baseline design, crew time commitment for maintenance using the Space Station robots is comparable or better than the EVA crew time conducting the same maintenance tasks. Robot and crew performance are greatly enhanced by the addition of on-board collision avoidance and remote control of the robots from the ground. An aggressive early use of these features should be considered for performing maintenance during the Space Station assembly phase in between Shuttle visits.

The Space Station Freedom robots are highly complex, but they are no more complex than previously flown space systems. Rigorous verification of the robotic hardware and software is mandatory and should be patterned after the successful verification practices used for the Shuttle flight control systems.

Creation of The ORU Database

The database created by this task team in response to the need to tabulate external ORUs is an essential reference tool for the program and should be continued. In addition, a common nomenclature for uniquely identifying each ORU does not yet exist, and should be developed and baselined throughout the Space Station Program. The ORU database enables rapid software incorporation of ORU updates and design changes as they occur, and can facilitate the development of a maintenance and logistics strategy for the Space Station.

Elimination of the "Pre-Breathe" Requirement

While not directly affecting the EVA external maintenance requirements, the lost crew time represented by the EVA pre-breathing for denitrogenation is unacceptable. Specifically, at least 10 man-hours are lost for each two-man EVA with the current plan for the Shuttle space suit (4.3 PSI) and a sea-level Space Station pressure (14.7 PSI). Obviously, this lost time increases directly as the EVA requirement increases. Members of this task team **strongly** advocate the elimination of the prebreathe overhead associated with EVA. This could be accomplished either by developing a higher pressure space suit or by lowering the baselined pressure of Space Station Freedom.

Problem Solving the Cause of Failed ORUs

If component reliability is going to improve with time on the Space Station, it is important that ORU failures be understood. Once the cause of the failure is determined, a decision can be made on any ORU improvements, weighing cost versus improved reliability. The EMTT could not locate a system for root-cause analysis and corrective action implementation of failed ORUs for the Space Station Freedom Program.

Recommendations

1. Develop a plan for accomplishing external maintenance requirements that will occur prior to the completion of Space Station construction.

2. Develop a logistics plan for Space Station that will place the required ORUs on Space Station both prior to its completion and during its 30-year lifetime.

3. Implement all recommendations by this task team for decreasing EVA overhead.

4. Develop a common design for all "box-type" ORUs, and require the implementation of that design uniformly across the Space Station Freedom Program.

5. Require that all external ORUs be replaceable in one hour or less by a single EVA crew member. Exceptions to this would be rare and made on a case-by-case basis.

6. Design all ORUs for mutual EVA and robotic compatibility with standard interfaces, and require implementation of that standard uniformly across the Space Station Freedom Program.

7. In addition to the robot autonomy currently baselined in the Space Station Freedom Program, implement collision-avoidance capability on board to reduce crew overhead for robotic operations.

8. Implement ground control of robots to further reduce crew workload.

9. Consider moving a large number of external ORUs inside, decreasing EVA requirements. Also, consider decreasing the total number of ORUs.

10. Baseline a root-cause analysis and corrective action implementation program for Space Station ORUs. Ensure that sustaining engineering supports reliability growth.

11. Eliminate the current EVA pre-breathe requirement, either by a higher pressure space suit or a lower pressure station.

12. Develop a preventive maintenance and inspection plan for the Space Station.

13. Place Space Station maintenance and logistics (including EVA and robotics) under a single command at a NASA center with work package responsibility.

14. Redefine the role of Space Station Freedom to reflect that of a "facility" rather than a "mission." Address the scheduling of regular periods of down-time for maintenance and refurbishment.

Findings

Findings

The EMTT effort addressed three major areas: the determination of the external maintenance required, an assessment of the EVA astronauts performing external maintenance, and an evaluation of the Space Station Freedom robots in performing external maintenance.

External maintenance consists of inspection, replacement of failed components, and preventive maintenance activities to prolong system performance levels or postpone component failure. The EMTT found that failed component or ORU replacement was by far the major source of Space Station Freedom maintenance requirements.

ORU replacement demand is a product of the number of ORUs in place on the Space Station, the expected failure rate of these ORUs, and the uncertainties in the definition of the environment in which these ORUs are required to operate. These three contributors to ORU replacement demand are addressed in the following sections under Failure Rate and K-Factor.

The amount of crew time required to replace the ORU is the sum of the crew effort required at the worksite to actually exchange the ORU (EVA worksite time) and the amount of crew time required to get to and from the worksite, with the necessary tools and spare ORU (EVA overhead time). Worksite time and EVA overhead are addressed in this section of the report in the discussions of Replacement and Repair Times for External ORUs and EVA Overhead.

Combining the ORU replacement demand and the amount of crew time required to perform the ORU replacement results in the total external maintenance demand being expressed in two crew member EVAs per year. This also can be expressed in man-hours and can thus be compared directly with the man-hours expressed in the October 1989 Cramer study. Derivation of the EMTT external maintenance demand for the 35-year life expectancy of the Space Station is addressed in the section on Demand Summary.

The assessment of Space Station Freedom robot performance was based on detailed discussions with robot and ORU designers. Sophisticated computer simulations were used to establish the robot equivalent of worksite time and procedures and the robot overhead required to get the robots to and from the worksites. Details of this analysis are presented in the section on Assessment of Robotic Maintenance Performance.

Alternatives to the baseline Space Station Freedom configuration were examined with emphasis on reducing external maintenance by relocating as many external ORUs as feasible to within the pressurized volumes of the Space Station. Other reconfiguration concepts were identified and recommended for further study. These reconfiguration alternatives and the significance of the logistics requirements for providing the spare parts necessary to meet the ORU replacement demand are addressed in the following section under Other Considerations.

ORU Count

In the Space Station Program Requirements Document, an ORU is defined as any part of the Space Station Freedom configuration that can be replaced on orbit.

At the beginning of the EMTT study, there was no overall estimate available for the total number of external ORUs for the Space Station. During the first pass of EMTT assessment, a total of 5578 ORUs were counted of 396 types and were classified into four categories in an attempt to understand the nature of external maintenance required. These four categories and their individual totals were Box (921), Electromechanical (296), Mechanical (2095), and Passive Structure (2466). The concept behind this kind of categorization was that the Box type ORUs would probably be the easiest to replace; Electromechanical would exhibit both random and wear-out failure tendencies; Mechanical would also be subject to wear-out type failures; and the Passive Structure ORUs would be long lived but require periodic inspection for micrometeoroid and orbiting debris impact.

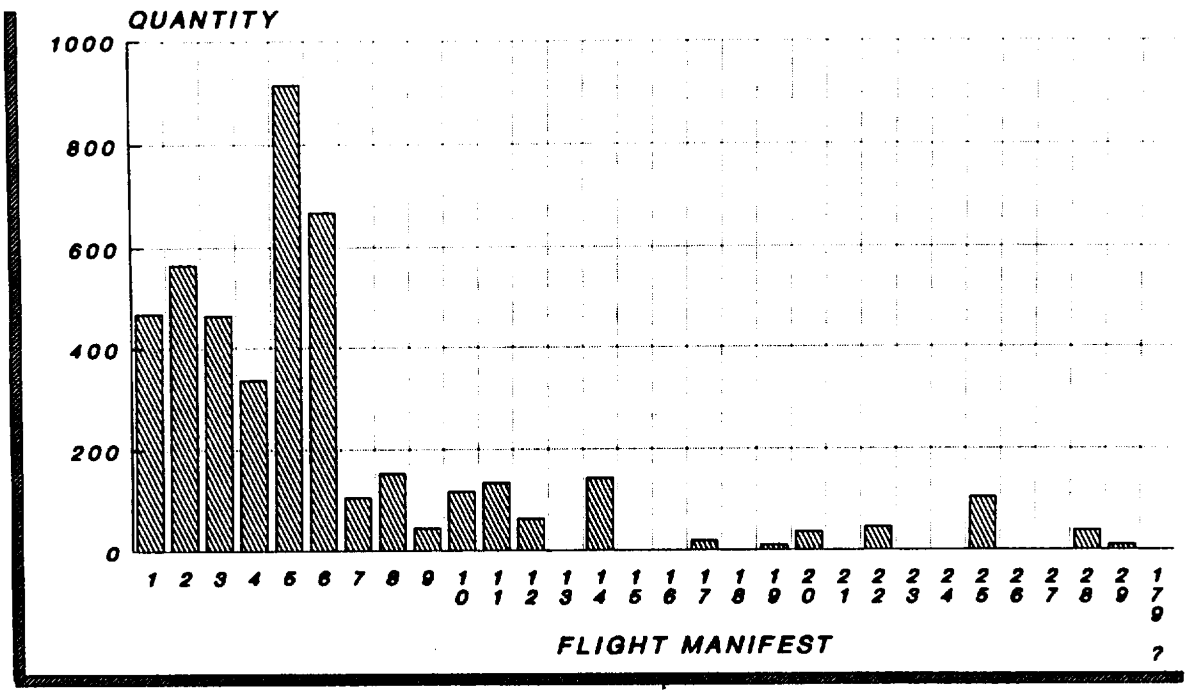
As more details of the ORU characteristics emerged, the EMTT found that the four categorizations were mixed in nature and were too restrictive in accomplishing the intent of defining both the nature of the ORU failures and the nature of the maintenance action required to replace them. The maintenance categories were revised to be Box, Device, Complex Assembly, Passive Structure, and Maintenance (to include actions other than replacement) and are so captured in the ORU Database.

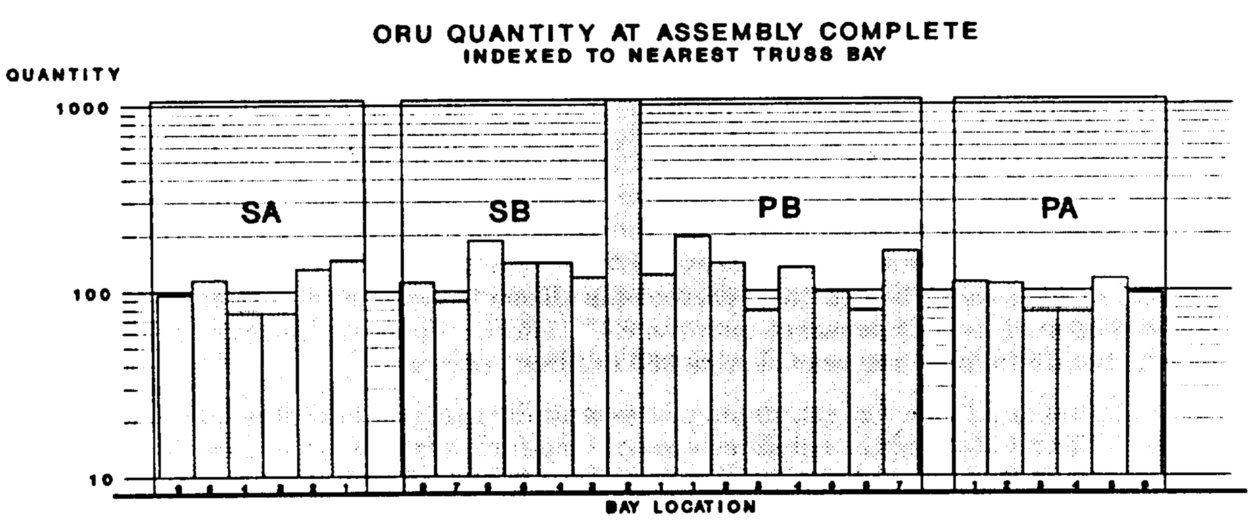
During the investigation of K Factor, a set of six ORU categories was determined to be necessary in order to understand the nature of failures resulting from causes other than inherent ORU failure rate. These reliability categories were Electronic, Electrical, Electro-Mechanical, Mechanical, Structural Mechanical, and Structural.

The SAIC effort which addressed both failure rate estimation and ORU count was instructed to use the reliability categorization convention. The total ORU count was determined by SAIC to be 8158, and these were categorized using the reliability categorization as Electronic (327), Electrical (1312), Electro-Mechanical (868), Mechanical (1046), Structural-Mechanical (3925), and Structural (680). These values are considered by the EMTT to best represent the current Space Station Freedom design.

In a separate process at the JSC, the assembly flight manifest for the ORUs and the locations of the ORUs on the Space Station were established for the first time. These determinations were based on the November 1989 assembly sequence and are summarized in the following graphs. Two conclusions can be reached from these graphs: most ORUs are on board the Space Station early in the assembly sequence, and the linear density of the ORUs along the truss bays is fairly constant except for a very high number of ORUs about the habitation module, ESA module, airlock, and resource nodes 1 and 3 located at Starboard Bay 2.

ORU'S BY FLIGHT





Failure Rate

Since the failure rate portion of the EVA demand time expression is a significant contributor to the final answer, it was important to make sure that this portion was not being grossly over- or underestimated. It was, therefore, decided to gage the values that were being developed, by the work packages and international partners, by comparing the Space Station Freedom design with other spacecraft that are now operating. To make this comparison, a team of consultants working under the direction of the Science Applications International Corporation (SAIC) was assembled.

The SAIC decided to make this comparison in two independent ways. First, they considered the types of ORUs that are in the Space Station that have electronic, electrical, or mechanical components. Purely structural ORUs were not considered because it was felt that the uncertainty of their failure estimates would not be a major problem. Using representative satellite data and data from other sources, they estimated the failure rates of typical ORUs with the above classes of components. Using the quantities of ORU types that are in the current Space Station design, an estimate was made of the failure rate of the station by appropriately proportioning the individual ORU estimates. This estimate is referred to as the synthesized failure rate estimate.

Next, SAIC selected several operational satellites for which failure histories are available. The Hubble satellite was chosen even though it had just been launched, and virtually no failure history was available. For the Hubble, design values were used. In addition, a nuclear submarine was also selected for study because it had many characteristics similar to the Space Station. The failure histories on these systems were also projected to the complexity of the Space Station by again proportioning these rate estimates by ratios of ORU counts. This estimate is referred to as the in-service estimate.

Comparisons of the synthesis and in-service estimates with the Space Station estimate are shown in Table 1. The mean estimates compare very closely. Moreover, when the uncertainty as given by the 5 percentile and 95 percentile is taken into account, it is seen that the Space Station estimate is well within the uncertainty limits of the comparative study. In other words, based on these comparisons, it appears that, on the average, the failure rates as determined from the work packages and international partners are in line with what is possible with our current technology.

The figure of .02 failures per hour in Table 1 computes to 175 failures per year. This is an average value and represents mostly failures due to random causes. When the other causes of failure are included (as will be discussed next), this figure will fluctuate over the life of the Space Station so that 175 represents an approximate lower bound on the number of failures. Also, the 175 does not represent the effects of K-factor (cf, Appendix D), which was developed in a study separate from the SAIC effort. When the K-factor (of 2.03) is included, the 175 failures per year become 355 failures per year.

The synthesis and in-service estimates also essentially represent failures due to random causes. The fact that today's satellites are not long-term systems, as will be the Space Station, means that our knowledge of their failures is limited and does not include much data on long-term wear-out effects.

Table 1
Comparison of Space Station Failure Rates with Synthesis and In-Service Estimates
(Rates are Stated as Failures per Hour)

	Mean	5 Percentile	95 Percentile
Synthesis	.038	.00075	.12
In-Service	.025	.006	.065
Space Station	.02	—	—

The next major activity was to refine our understanding of the way the failure rates might behave over the life of the Space Station. For the January 1990 estimate, for the most part, only constant failure rates were estimated. This means that the projected failures would be evenly defused over time so that one would expect to see about as many failures early in the life of the Space Station as would be seen late in its life. Constant failure rates are often associated with random causes and many times serve as good models for purely electronic components. Normally, however, in most complex systems, failures do not occur this evenly in time. Quite often as a system begins operation, a large number of failures are seen due to problems in the manufacture and operation of its components. These types of failures are often referred to as infant mortality failures. Later in the life of a system, components begin to wear out, and, as a result, the number of failures begins to rise. These are the so-called limited life failures.

In addition to making the above comparative estimate of the Space Station failure rate, the SAIC team was also given the task of visiting the work packages and some international partners and working with the designers of the ORUs to split the failure estimates into infant mortality, random failure, and limited life parts. Since many of the ORUs are in the early design stages, this kind of a refinement in the failure rate could not be performed reliably on each ORU. Consequently, it was decided that the ORU categories established for the comparative studies should also be used for this study. These categories are electronic (ET), electrical (EE), electro-mechanical (EM), mechanical (ME), structural-mechanical (SM), and structural (ST). The last two categories, structural-mechanical and structural, were added to account for all types of ORUs on the Space Station. Because the final projections of EVA demand time are projections of expected (i.e., average) times, placing the ORUs into these large category groupings to analyze failure rate was considered reasonable.

Figure 1 shows the time history of the failure projections over the 35-year life of the station. (The effects of K-factor are included in this graph, even though K-factor was not part of the original SAIC estimate.) The graph shows the peaks and valleys in the number of failures due to the phasing of infant mortality, random, and limited life failures. The graph also shows the effect of the sequence with which the various ORUs will be placed in operation on the Space Station. The combination of this buildup of ORUs and infant mortality shows that in the second year, a peak in the failure rate of about 480 can occur. The failures then begin to settle down until about the eleventh year when an 11-year cycle of limited life failure begins to occur. The limited life failures vary between about 870 and 780 per year.

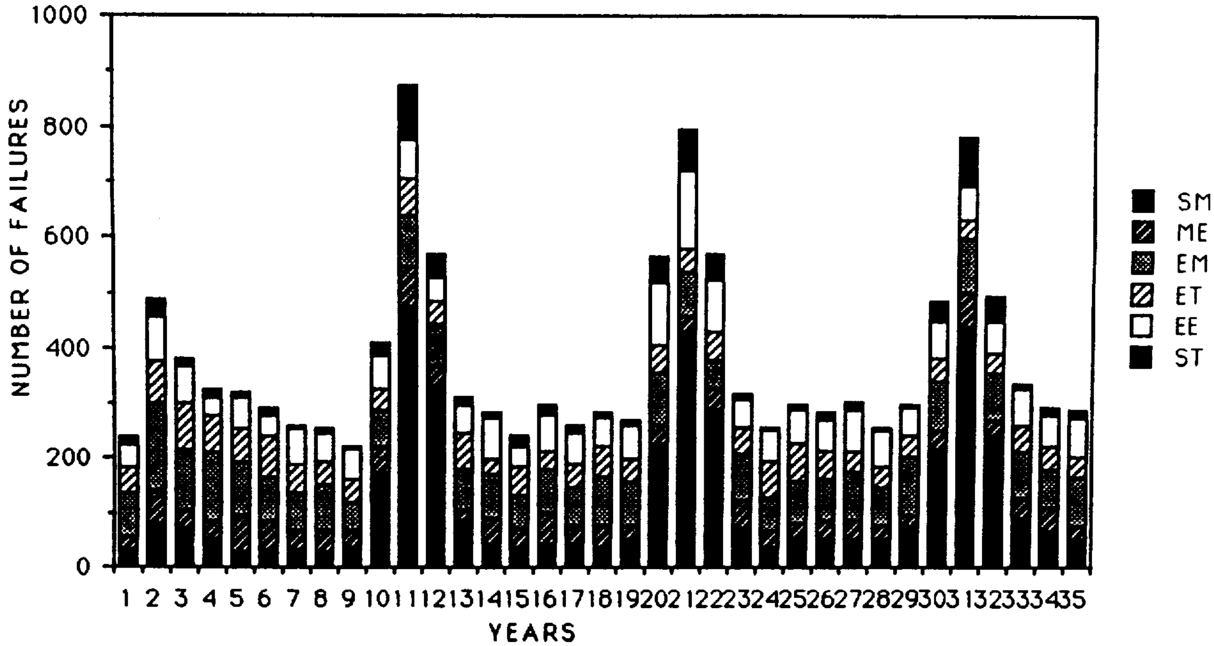


Figure 1. Failure Profile

Once the SAIC team collected all its findings on failure rate, these findings were reviewed by a blue ribbon panel of experts representing reliability, statistics, system design, and other disciplines. This team agreed with the SAIC findings and made several recommendations regarding the Space Station design. These are included in the Recommendations Summary section.

Space Station Freedom Replacement and Repair Times for External ORUs

General Definition of Terms

The replacement (or repair) time for an ORU refers to the time actually spent at the worksite performing the replacement task. It does not include any aspect of non-worksite time such as EVA overhead nor does it include K-Factor.

Background

Once an external Space Station ORU has failed, its replacement or repair time becomes a key parameter in determining EVA External Maintenance Requirements. To separate the actual time required to replace a given ORU from the overhead time required to get the crew member to and from the worksite, the concept of mean time to repair (MTTR) was utilized.

This separation is necessary because even though the EVA overhead associated with a given task is relatively constant, the times required to effect actual ORU replacement or repair vary widely from task to task. This variation is dependent on such factors as the number of actions, the type of actions, the location of the ORU, the size and shape of the ORU, and the number of crew members required for ORU replacement. Separating the actual replacement time from the rest of the EVA, enables a task analysis on a step-by-step basis for each of the external ORSs on Space Spation.

Methods

In our preliminary analysis, one of the goals of the EMTT was to obtain current estimates of the replacement times for each of Space Station Freedom's external ORUs. This information was requested from each of the work packages and international partners in January 1990.

While most responded with an estimated time, it became clear that there was no consistent definition of what "mean time to repair/replace" meant within NASA. To some work packages, it meant actual time at the worksite, but opinions varied as to whether or not this included a functional checkout of the ORU after the replacement activity was complete. To others, it included portions of EVA overhead or K-Factor. In many cases, it was also unclear whether one or two crew members were required for the replacement activity.

It also became apparent that no two work packages or international partners had a common way of estimating how to extrapolate "shirtsleeve" replacement time on Earth to space-suited astronaut replacement time in microgravity. Some work packages had personnel who had worked with suited astronauts and had varying degrees of experience in making such judgments. Others took the time required to perform the replacement by a technician on Earth and multiplied this figure by a constant. Several stated that they had made the best educated guesses possible. In general, while there were no wide variations among the work packages, each had arrived at an answer using different methods and assumptions.

After the initial data-gathering phase of its study, the EMTT concluded that a meaningful analysis of the ORU repair/replacement times would require three key elements.

1. A common definition of the ORU repair time. Specifically, which activities should be considered "repair time" activities and which were "EVA overhead." This definition would then be applied uniformly across all NASA elements involved with Space Station Freedom design.
2. The availability of detailed engineering drawings for all ORUs.
3. A step-by-step listing of each task necessary to complete the ORU replacement or repair. Since no task is trivial in a pressurized space suit, this task listing would need to be detailed down to a "nuts and bolts" level.

The EMTT subsequently developed a proposed standard definition of what activities were to be included in ORU repair/replacement time estimates. This definition was discussed with representatives from all work packages and international partners during a Space Station Freedom external maintenance meeting at JSC, on April 17-19, 1990. The final definition presented at the close of that meeting is as follows:

Definition

Space Station Freedom ORU Replacement Time

> ORU replacement time begins with the EVA crew member in the required restraints at the worksite, the failed ORU in place, the new ORU temporarily stowed at or near the worksite, and the required EVA tools tethered to the crew member or in the immediate worksite area.
>
> ORU replacement time ends with the EVA crew member in the required restraints at the worksite, the new ORU installed, the failed ORU temporarily stowed at or near the worksite, and the required EVA tools tethered to the crew member or in the immediate worksite area.
>
> ORU replacement time includes EVA tether protocol, EVA checkout of the completed procedures, and any other steps between the beginning and ending configuration.
>
> ORU replacement time is counted as clock time to perform the task, and is independent of the number of EVA crew required. The resulting increase in man hours required if two EVA crew members are needed to perform a task will be accounted for separately.
>
> All activities not included in the above definition will be considered as "EVA Overhead."

To enable the analysis of EVA ORU replacement tasks, representative ORUs were selected. These included ORUs which, because of their relatively large number, generic nature, or complexity, were believed to best represent a cross section of maintenance requirements within a given work package.

A list of the identified ORUs was then sent to the responsible parties within the Space Station work packages. With this list went a request to identify every step necessary to effect a replacement or repair of the ORU in question.

When the requested information was returned to the EMTT headquarters in Houston, it became clear that the detailed timeline analysis of most ORU replacement tasks would not be possible. While a general sequence of events for a given replacement could be provided, the majority of ORU designs were not sufficiently mature to permit a step-by-step replacement scenario. In some cases, a rough understanding of ORU architecture, geometry and design existed, but for some ORUs not even a sketch could be provided. In the majority of cases, the approximate replacement timelines had been created in response to the EMTT request.

In most instances, the work package representatives explained the lack of detailed information by pointing out that the preliminary design review for Space Station Freedom would not occur until later in the year, and that the type of design information being requesting would not be available until then.

Analysis of the Data

Although ORU design immaturity prevented the EMTT from obtaining the level of replacement time accuracy intended, pursue three separate analyses on the work package data were pursued. The first involved scrubbing all the ORU replacement time data to ensure that EVA overhead and K-Factor had not been included in the estimates. The second required a clear understanding of whether one or two EVA crew members were required in the ORU replacement. The third was to separate any steps that were known to exist in an ORU replacement activity and compare them with similar actions already present in the Space Shuttle Program EVA inventory.

As an example of the latter activity, while the specific design of a Space Station Freedom ORU may not be available for analysis, it might be determined that a pump must be removed as one of the steps involved in replacing this ORU. There are existing detailed instructions for a pump removal within the Space Shuttle Program EVA procedure inventory. Using the Space Shuttle EVA procedures, some insight can be gained into what might be required on Space Station. If enough of these analogous procedures could be identified within the expected ORU replacement activities, the EMTT felt it was possible to perform a "sanity check" on the Space Station ORU replacement time estimates.

To perform this analysis, the task team had two good resources. One was the composition of the core team itself: three members had extensive EVA or EVA planning experience. The other was the EVA Branch of the Mission Operations Directorate (MOD) at JSC. This group is responsible for the planning of all aspects of Space Shuttle EVA activities, and represents the broadest and most experienced EVA group within NASA.

Results

A review of all available analogous data was performed and, where possible, applied to the estimated Space Station ORU replacement times for the representative ORUs selected. Through this analysis, the majority of the worksite times decreased; but many uncertainties still remain. Design immaturity greatly hampers accurate timeline development, and the issue of on-site ORU checkout has not been addressed. Because of these uncertainties and the fact that the history of spaceflight equipment shows that this equipment becomes more complex as the design matures and requirements solidify, the estimates from the work packages were used as the baseline. These estimates appear in Appendix C, and have been scrubbed of all K-Factor and EVA overhead activities. Requirements for a one or two crew member EVA are not reflected in this data, but are a part of the ORU Database and are accounted for algorthmically in maintenance calculations.

As designs solidify, closer analyses obviously will be possible, and it is expected that any changes to the ORU replacement timelines will be entered as updates to the ORU database.

Worksite Time Recommendations

1. Formally adopt the EMTT definition of Space Station ORU replacement time across the entire Space Station Program.

   Definition

   Space Station Freedom ORU Replacement Time

   ORU replacement time begins with the EVA crew member in the required restraints at the worksite, the failed ORU in place, the new ORU temporarily stowed at or near the worksite, and the required EVA tools tethered to the crew member or in the immediate worksite area.

   ORU replacement time ends with the EVA crew member in the required restraints at the worksite, the new ORU installed, the failed ORU temporarily stowed at or near the worksite, and the required EVA tools tethered to the crew member or in the immediate worksite area.

   ORU replacement time includes EVA tether protocol, EVA checkout of the completed procedures, and any other steps between the beginning and ending configuration.

   ORU replacement time is counted as clock time to perform the task, and is independent of the number of EVA crew required. The resulting increase in man hours required if two EVA crew members are needed to perform a task will be accounted for separately.

   All activities not included in this definition will be considered as "EVA Overhead."

2. Develop detailed ORU designs as soon as possible, so that more accurate EVA replacement timelines can be developed.

3. Have all ORU replacement times developed by the EVA Branch of the Mission Operations Directorate at the NASA Johnson Space Center, using procedures supplied by the

individual work packages. These times would then be entered into the database for that ORU, and would be the sole source of its replacement time data.

4. Baseline all ORU designs to allow for end-to-end replacement in one hour or less by a single EVA crew member. Exceptions to this should be rare and allowed only on a case-by-case basis.

5. Standardize ORU design and EVA tools wherever possible. Individual work packages and international partners must be required to conform to a common set of ORUs and EVA tools where design and function permit. (This activity was initiated in March 1990 as part of the EMTT effort, see Appendix G).

6. Incorporate into the design of each ORU a rapid means of functional checkout after replacement is complete.

K-Factor

General Definition of Terms

The K-factor is that factor which takes into account otherwise unplanned events in equipment maintenance. Specifically, it allows for increased equipment maintenance actions which have not been included in the failure rate estimates for that item.

The K-factor is expressed as a numerical value, and is used as a direct multiplier to equipment failure rates. For the purposes of this study, K-factor does not include preventive maintenance, inspection, and overhead rates or times.

A good example of this concept might be seen in the automobile mechanic who is changing the air conditioning compressor on a car. He may drop the new compressor prior to installation, breaking it and requiring its replacement. He may install the new compressor in place, only to find it doesn't work. After completing the installation, he may find it wasn't the compressor after all that was causing the problem, but rather an electrical switch which will need replacement. Finally, he may puncture a radiator hose in the process of replacing the new compressor, requiring the subsequent repair of a different system. Each of these unexpected and unplanned for events would fall under the heading of K-factor.

Background

In September 1989, an investigation into Space Station Freedom external maintenance requirements, chaired by Dr. Bryant Cramer, revealed the need for the application of K-factor in making repair time estimates. They found that while many of the Space Station work package elements shared this view, there was a wide variation across the program with regard to the definition, application and quantification of this factor.

For the purposes of that report, a K-factor value of 2.0 was agreed to, with the addition of 0.3 to account for anticipated preventive maintenance. The resulting value of 2.3 was then designated "K-factor," and was used as a direct multiplier to the calculated EVA requirement in determining a total number of required hours.

In the EMTT's initial evaluation of the Space Station external maintenance requirements in February 1990, we also chose to use the K-factor value of 2.3. It not only afforded a direct comparison between our estimates and those of the Cramer study, but it was consistent with findings in the aerospace industry.

It was clear, however, that an in-depth assessment of the nature and value of K-factor in the Space Station environment was necessary to accurately define the total external maintenance requirement.

The demand expression for calculating the overall maintenance requirements is as follows:

Total External Maintenance Time

Expected Maintenance Time =

$$\sum_{1}^{6} \left(\text{Generic No. of Failures/Class}\right) \left(\text{K-Factor}\right) \left(\text{Expected Replacement Time}\right)$$

Generic No. of Failures/Class: Estimated by "Monte Carlo" simulation Includes effects of

- # ORUs
- Failure Rate
- Duty Cycle

K-Factor: Estimated by Contractors + JSC and has the form $K = K_1 + K_2 + K_3 + K_4 + 1$

Expected Replacement Time:

- MTTR estimated by contractors
- EVA overhead estimated by JSC

X000890M

Methods

To better estimate K-factor, the ideal analysis would consider the characteristics of each individual ORU (such as failure rate and location). Since that information was not sufficiently mature to be incorporated into the EMTT effort, the external ORUs on Space Station Freedom (SSF) were divided into six different classifications. This was felt to be necessary, because certain pieces of equipment, such as structural support members, will differ from electrical components in the frequency and nature of unplanned maintenance.

The six categories are based on equipment design characteristics. These categories are defined in the ORU Database as equipment "Reliability Types." All equipment is classified within one of the following categories:

Electrical (EE)

Electrical-mechanical (EM)

Electronic (ET)

Mechanical (ME)

Structural (ST)

Structural-mechanical (SM)

The following criteria have been used to characterize the historical aircraft and current SSF equipment. These criteria are to be used to categorize newly developed Space Station equipment in the future.

Electrical: Electrical equipment is that which performs electrical power distribution or storage functions, signal distribution, or radio frequency radiation functions and less than approximately 5% of the failure rate is due to digital or low-power electronics or moving parts. Typically, electrical types are selected where a low level of BIT is utilized.

Electrical-Mechanical: Electrical-Mechanical equipment is that which contains both electrical/electronic and mechanical moving parts. This includes devices which typically utilize electrical energy to produce mechanical motion and those which use mechanical energy to produce electrical power or signals. These devices should contain more than 5% of mechanical and 5% electrical (or electronic) parts (based on failure rate).

Electronic: Electronic equipment is that which is primarily digital or analog circuitry in nature and has a greater need for BIT than the electrical type. The equipment is classified as electronic only if less than 5% of the failure rate is due to moving parts.

Mechanical: Mechanical equipment is that which typically consists of moving parts, or contains fluids or seals. This type of equipment must contain less than 5% of the failure rate due to electrical or electronic parts. Heat transfer equipment is classified as mechanical.

Structural: Structural equipment is that which is load bearing and less than 5% of the failure rate is due to moving parts or sensory components. (However, a moving part may be contained within a structure if the moving part is a separate piece of equipment.) Structure, as defined in this study, is further characterized as typically not having crew contact. It is noted that the truss struts will occasionally be used by crew members during translation. However, since the struts are being designed to accommodate inadvertent impacts and loads which can be produced by humans in space suits, they are being classified in the structure category.

Structural-Mechanical: Structural-Mechanical equipment is that which is mostly structural or designed for equipment protection and typically involves crew interaction. This type specifically includes items such as doors, covers, panels, meteoroid/debris shields, thermal blankets, handrails, foot restraints and other equipment involving frequent crew contact. The main difference between structural and structural-mechanical is that the latter contains moving parts and/or fasteners which are inherently more vulnerable to damage during human contact.

The following methodology was used to develop K-factor values for the equipment types.

A) Defined K-factor elements/subelements and the K-factor equation.

B) Gathered and evaluated historical data on aircraft equipment maintenance and categorized the equipment and data by K-factor elements/subelements.

C) Summed K-factor element/subelement values for each equipment type (i.e., control panels, heat exchangers, valves, actuators, controllers, etc.).

D) Grouped historical equipment into classifications and averaged the K-factor subelement values to yield representative total subelement values.

E) Defined equipment classifications (i.e., mechanical, electrical, structural, etc.) based on reliability types for various Space Station equipment.

F) Developed and applied correlation factors for human error and false maintenance rates to the historical aircraft K-factor subelements to yield a SSF equipment equivalent.

G) Developed the K-factor subelement values for environment-induced, equipment-induced and access-caused maintenance actions.

H) Established a matrix reflecting the various subelement and total K-factor values for each reliability classification type.

Human Error Subelement (K1)

The K-factor subelement K1 accommodates occurrences when equipment is inadvertently damaged due to misuse, improper maintenance and incidental contact. Causes for human error include such things as visibility/perception, dexterity/mobility, comfort, fatigue and physical orientation. Training and motivation have been noted as being contributors to human error. For purposes of this study, however, it was assumed that personnel working on Earth were equally trained and had equal motivation in performing their tasks. Only physical differences were reviewed in this correlation. The human error rates estimated were developed using a two-step approach. The first step was to evaluate historical data pertaining to human error rates. The second step was to ascertain how the space environment (using a Shuttle space suit) was different compared to the work environment on Earth. This difference created a correlation factor which was applied to the historical data to develop SSF estimates.

To accommodate human error in the space application, a correlation survey was used. This survey is included as an attachment to Appendix D. In correlating the data, a range of 0 to 2 was used for the "Environment Comparison Evaluation" portion of the survey. Accordingly, if the human error element was the same for space as on the ground the "same" category was circled and a value of 1 was applied.

The survey was distributed to several groups of people ranging from design and human factors engineers to astronauts with EVA experience. Responses to the survey varied; however, the unanimous opinion was that the space environment is a more difficult place to work. Results of the survey produced a range from a 10 percent increase to an 80 percent increase of human-error potential. Upon review of the results, it was noted that persons with actual EVA experience considered the two environments quite similar. Typically, the design and human factor engineers were less optimistic in their opinions. Because there was such a large range of opinions, it was decided that the human-error correlation factor given by EVA experienced personnel would be pursued for this study. Accordingly, a 1.10 correlation factor was used.

The survey was deemed somewhat vague because people have different interpretations of the human-error elements. To improve consistency of the results, specific definitions should have been included in the survey instructions. Also, many responses indicated that specific maintenance tasks should have been considered to allow for a better evaluation. However, the purpose of the survey was to evaluate maintenance activities in general.

Environment-Induced Subelement (K2)

The K-factor element K2 accommodates maintenance rates caused by natural environment effects. The natural environments defined in SSP 30425 and SSP 30420 were used as a basis for the environmental assessment of this study. Reliability references (MIL-HDBK-217E and Rome Air Development Center-Reliability Engineer's Tool Kit) were reviewed to determine which of the various environments were accommodated in the mean-time-between-failure (MTBF) calculations. Results of the review indicated that environments, such as oxidation, thermal, vibration and pressure (atmospheric and vacuum), were accounted for in the MTBF predictions. However, two environments (micrometeoroid/space debris and ionizing radiation) were not contained in these predictions. Accordingly, these two environments have been included in the K-factor K2 subelement assessment. The following section describes these two environmental factors.

Micrometeoriod and Space Debris. Micrometeoroid and space debris could have substantial impact on the Space Station if protective equipment falls short of requirements. Currently, substantial efforts are underway to assure that critical SSF equipment is protected to the level specified in the program requirements. The requirement states that the probability of no penetration (PNP) for critical equipment (assumed as Critical 1S equipment) over a 10-year period, must be .9955. A PNP of .95 for non-critical equipment (assumed as all other equipment) has been assigned for purposes of MTBF predictions. Even though there are no requirements for non-critical equipment, a level of .95 appears reasonable and achievable.

Ionizing Radiation (IR). Ionizing radiation (IR) has unique effects on various categories of equipment. It is known to degrade seals and lubricant properties, break down bonding of composites and cause both electron migration (over time) and single-event upsets (due to solar flares) within electronic component software programs. Because there is much statistical uncertainty associated with the IR phenomenon, the effects of IR have been estimated for each equipment category using engineering judgment. This method was used because information has been quantified to date to aid in the development of better estimates. It is expected, however, that with further evaluation of the Long Duration Exposure Facility (LDEF) test results, more definitive and substantiated data will become available over the next year.

To accommodate the uncertainty, and for purposes of this study, the following IR environment values for K2 have been used. Mechanical and electrical types of equipment have been estimated at 0.02. This is based on seal and lubricant degradation with associated contamination potentials. Structural and structural-mechanical equipment have been deemed least affected by IR. In fact, with the current SSF strut and longeron design baseline (composite structure within an aluminum layer), no appreciable IR degradation is expected for the entire 30-year life of SSF. Accordingly, structural and structural-mechanical types of equipment have been estimated at 0.00 for IR effects. Electrical-mechanical types of equipment have been estimated at 0.05 based on seal and lubricant degradation with associated contamination potentials. Note that this rate is greater than the mechanical and electrical types mainly because of the increased quantities of equipment containing seals and lubricants in this reliability type category. Electronic types of equipment have been deemed the most susceptible to IR effects. Software programs can be adversely affected (over time) due to the occurrence of electron migration and electrical property degradation. Also, because random single-event upsets can occur due to intense solar flares, an estimate of 0.10 has been used for electronic equipment types.

It can be noted that when electronic controller software has been affected, the corrective action is to reload the programming. The other equipment types will typically require replacement after sustained IR degradation.

Equipment-Induced Subelement (K3)

The K-factor element K3 accommodates maintenance rates caused by equipment malfunctions/failures which in turn cause other interfacing or surrounding equipment failures. The K3 values have been established using aircraft historical data as a basis. This data is appropriate for Space Station equipment use mainly because the design requirements are the same. Both aircraft and Space Station requirements state that failures of one piece of equipment must not cause a failure of another piece of equipment. To accommodate this fail-safe feature, shielding, partitioning, protective devices, and similar items are implemented at system and component levels. To verify the implementations, extensive analyses and testing are performed.

As shown in the various historical data sheets included in Appendix D, the extent of equipment-induced failures has been negligible (less than 1 percent). Accordingly, it can be projected that Space Station equipment will also exhibit these same characteristics. And, to accommodate a potential for any such occurrences a value of 0.01 has been assigned for each equipment category. Note that this is the result of rounding up to the nearest two decimal places.

No-Defect Rate Element (K4)

The K-factor element K4 accommodates maintenance rates caused by false alarms/incorrect fault isolation and in-the-way removals to gain access for other equipment maintenance. Each of these is considered a subelement. The false alarm and incorrect fault isolation element rate was developed using a two-step approach. The first step was to evaluate aircraft historical data pertaining to these items. The second step was to ascertain how aircraft automatic built-in test (BIT) design compares to the Space Station equipment BIT philosophy and design. The subelement of in-the-way removals (or access-caused maintenance actions) has been estimated based on Space Station-specific equipment design. This is because the SSF program requirements state that equipment shall not be removed to gain access to other equipment; whereas, based on current information, the aircraft programs reviewed in this study have no such requirement.

The following sections provide the methodology and rationale used in developing the no-defect subelement values.

False Alarm/Incorrect Fault Isolation. Automatic BIT for the SSF systems and equipment should exhibit a more reliable effectivity rate than the rates documented in the historical data sheets.

The design activity for the BIT of the most recent historical data herein is 8- to 10-year-old technology. Advancements in BIT development techniques, hardware and software technology, and improvements in requirements definition have indicated on more recent programs (programs such as the F-15E and F-18, for which limited data is available) that BIT and built-in test equipment (BITE) capabilities have experienced continued improvement. The trend clearly is more effective BIT results.

The use of better design techniques have improved BIT effectivity. Continuous BIT monitoring makes use of real-time, run-time operational functions for unambiguous fault detection and isolation. One function, or operation, or capability is monitored by dedicated BIT/BITE. As this is the least complex design for BIT, there is less change of BIT errors. When a failure is detected, BIT routines are designed to repeat before declaring a failed asset. This reduces fault declarations as a result of transients or one time anomalies. BIT design is now concurrent with hardware/software design, not something that is added on after prime circuitry has been developed. This allows for earlier use of BIT (i.e., in the integration labs, on the manufacturing floor, etc.) and provides for extensive debugging before BIT is deployed. Also, hardware topology has matured to the extent that certain hardware functions are implemented in similar or exactly the same manner as on other systems. For example, a digital pulse-counting ciruict is the same on an amplifier as it is on a computer. Repeated use of hardware topology has allowed a maturation process of the test strategy for that hardware. Newer systems utilize "lessons learned" from older systems.

Implementation of BIT in hardware versus software has improved effectivity. The use of hybrids and gate arrays with on-board (chip level) test capability has removed many "software faults" from the list of BIT failure mechanisms. Hardware is easier to troubleshoot and maintain than software. Also, improvements in manufacturing processes for prime equipment have eliminated many failure mechanisms that were very difficult to isolate with built-in test. The use of multi-layer core boards (PWBs) and automated soldering techniques have greatly reduced ambiguous failure indications due to manufacturing flaws.

Requirements definitions have evolved simultaneously with BIT design. More detailed requirements, using clearly defined capabilities with exacting parameters have removed "interpretation" problems that generally manifest themselves in less than optimum design. The BIT effectivity analysis techniques have required the efficient development of BIT.

All of the previous discussion justifies optimism in BIT capabilities. Accordingly, a decrease in maintenance actions should occur compared to aircraft historical data. The amount of decrease, due to improvements in automatic isolation, is estimated at 10 percent. Therefore, the correction factor for equipment which has BIT is 0.90. Equipment in this category includes electrical, electro-mechnical and electronic equipment types. The other types of equipment (structural, structural-mechanical and mechnical), which typically do not utilize BIT, will be subjected to manual fault-isolation techniques. These techniques, along with the associated test equipment, are considered similar in both aircraft and spacecraft equipment. Therefore, the equipment which typically requires manual testing will have a correlation factor of 1.00.

In-The-Way Removals. The K-Factor K4 subelement value for access-caused maintenance actions is dependent on specific Space Station equipment design. In cases where the equipment under K-Factor evaluation must also be disturbed and/or removed to allow access for other equipment maintenance, this additional K-Factor subelement value has been developed and incorporated into the total no-defect rate element value. Also, an additional value is necessary for inclusion in that equipment's K2 because each time a piece of equipment is handled, there is a potential for damage. To accommodate this, the equipment's human-error-induced damage rate is to be used. The access-caused action value is developed by determining the failure rate relative ratio of the equipment being handled to gain access to the equipment being evaluated for K-Factor value. The additional value for human-induced failure is developed by multiplying the preceding ratio by the equipment's appropriate human-induced (K1) value. To illustrate this concept, observe the following example:

Example: Given a piece of equipment under K-Factor evaluation, E(1), which has a failure rate of 100 and must be removed occasionally to allow access to a failed item, E(2), which has a failure rate of 10, the access ratio of 10/100 or 0.10 is produced. This ratio is then the K4 value of the K-Factor. Now, given the item E(1) has a human-error-induced damage rate of 0.20, the addtional human-error value is 0.10 x 0.20 = 0.02. This 0.02 is then added to the original human-error value to yield the actual rate at which the equipment will need replacing due to the inherent rate of contact plus the access-caused rate of contact.

Access-caused rates are typically low due to the SSF Program requirements. Accordingly, values of 0.01 have been assigned to the mechanical, structural, electrical and electro-mechanical equipment categories. Structural-mechanical equipment has been assigned a value of 0.00 because of the definition used in this study (i.e., equipment which provides protection and is typically displaced to gain access for other equipment maintenance). The electronic equipment category has the highest estimated access-caused rate because almost all electronic equipment is mounted on somewhat complex cold plates. This type of mounting scheme is necessary to meet the thermal performance requirements. Since electronic box types are the largest portion of electronic-configured equipment on SSF, an overall value of 0.10 is being used for the K4 access-caused rate.

Results

The following presents the equpment K-Factor summary. Each equipment category (based on reliability type) is shown with its associated K-Factor subelement values and total K-Factor value. The weighted overall K-Factor for this particular study was 1.88. When individual K-Factors are used to compute the reliability class values, however, the effective average K-Factor is 2.03.

The ORU Database contains items identified as "MAINT.TYPE" = maintenance. The entries represent life changeout, equipment cleaning (camera lens, windows and similar items) and some in-situ repairs. Since these are considered scheduled maintenance events, to a large extent, it has been assumed that the "MTBF" listed is really a mean-time-between maintenance actions (MTBMA). Therefore, by definition, a K-Factor value of 1.00 has been applied to these items. To account for the human-error-induced damage potential which occurs during the scheduled maintenance events the error damage rate has been included in the corrective maintenance term of the equipment. That is, the rate has been included in the K1 value term which concides with the inherent (random) failure expression in the database.

Equipment K-Factor Summary Matrix

EQUIPMENT RELIABILITY TYPE	HUMAN-ERROR-INDUCED RATE (K1)	ENVIRON-MENT-INDUCED RATE (K2)	EQUIP-MENT-INDUCED RATE (K3)	NO-DEFFECT RATE (K4)		TOTAL K-FACTOR VALUE*
				FALSE/ INCOR-RECT MAINT. RATE	ACCESS-CAUSED RATE	
MECHANICAL	0.31	0.50	0.01	0.32	0.01	2.15
STRUCTURAL	0.46	0.00	0.01	0.26	0.01	1.74
STRUCTURAL-MECHANICAL	1.76	0.00	0.01	0.34	0.00	3.11
ELECTRICAL	0.19	0.07	0.01	0.23	0.01	1.51
ELECTRO-MECHANICAL	0.34	0.10	0.01	0.36	0.01	1.82
ELECTRONIC	0.12	0.15	0.01	0.41	0.10	1.79

* Based on Use of K-Factor Equation

Results and Conclusions

The following results and conclusions can be made based on the findings of this study.

1. K-Factor is shown to be a substantial factor when considering total maintenance demands. Human-induced maintenance rates and false maintenance rates have historically been shown as the major drivers. The methodology used to develop the equipment type K-Factor values was based on a solid approach. The methodology allows future equipment K-Factor assignments to be made with minimum effort and provides reasonably good results. It can be stated with a high level of confidence that if the K-Factor evaluations were performed down to a specific equipment level (i.e., a unique K-Factor value for an antenna, valve, heat exchanger, cable, etc.), that the overall results would not change more than a few percent.

2. As demonstrated in the K-Factor summary section of this report, certain equipment types exhibited large K-Factor subelement values. These "heavy hitters" are summarized as follows:

   - Structural-mechanical equipment exhibits a high human-induced damage rate.
   - Mechanical equipment exhibits a high environment-induced damage rate.
   - Electronic equipment exhibits high environmental and no-defect removal rates.

3. The total K-Factor value (for the various equipment type categories) ranged from 1.51 to 3.11, with an effective average of 2.03. This range is consistent with what has been repeatedly verified on major programs in which maintenance data have been tracked. Also noted was the fact that there was a minimal variation between the values of specific equipment types within a given category. The standard deviations of equipment values within each category were all around 0.2. This, therefore, demonstrated appropriate equipment selections in each of the equipment category groupings.

4. The amount of unmanned and manned spacecraft experience data was found to be negligible and/or not readily quantifiable. Some equipment-induced and environment-induced data exist, but not enough to provide useful correlations. Environmental data are currently being quantified via LDEF studies, but were not available at the time of this study. Shuttle data indicated that equipment-induced occurrences do exist however, they are sparse and sporadic. Accordingly, it was decided to use a Space Station-specific equipment design approach and provisions to estimate the equipment-induced rate.

5. During the course of this study, it was acknowledged that equipment location could potentially drive the K-Factor to different values. The difference would be mainly attributable to human and environmental effects. However, upon further evaluation the differences appear negligible compared to the current K-Factor values. Rationale for not distinguishing and using equipment location effects is as follows:

   - Human-induced causes are already included in most of the equipment types (i.e., control panels, covers, doors, etc.) which have moderate human contact over time. These types of equipment are inherently exposed to human interface and, therefore, do not need to be increased to account for a greater damage potential.
   - Environmental effects between the zenith, nadar and velocity vector orientations will be somewhat different. However, considering that for every piece of equipment with greater exposure, there is another piece of equipment with less exposure, an

average rate appears applicable. Also, because of the current SSF equipment protection design approach (using appropriate shielding), equipment located predominantly in more vulnerable locations is being designed for greater protection to achieve the required probability of no penetration.

6. The method being used to consider access-caused maintenance actions is appropriate for use at this stage of SSF development and produces reasonable results. However, a more accurate method in estimating the EVA demand, which is being implemented as mean-time-to-repair (MTTR) detailed task analysis capabilities are developed, can be used at a later date. This other method inherently yields better estimates because MTTRs are developed on a specific equipment case-by-case basis; whereas the K-Factor is being developed for more generalized equipment categories. If MTTR is used at a later date, then the K4 value for access-caused maintenance actions can be omitted. However, the portion accounting for equipment damage due to human error would remain, regardless of which method was used.

Recommendations

The following recommendations are made based on the results of this study.

1. Results of the EMTT should be used to provide design direction for various SSF equipment. If emphasis is applied on the items driving K-Factor values, reduced EVA demand will result. A prime example would be to ruggedize access covers, panels, mounting guides, and connecting fasteners to reduce human-induced damages of the fastening mechanisms and attaching hardware. This should be considered necessary because, historically, damage rates for similar types of equipment are shown to be a major factor in causing additional maintenance actions. Accordingly, establish and quantify test requirements for the program.
2. A detailed study of human error correlations should be performed to gain better understanding of drivers which cause humans to err in the space environment. Once the drivers are singled out, design efforts should be made to accommodate and reduce the causes. A detailed study is recommended because human-error-induced rates are a significant portion of the overall K-Factor totals.
3. With the appreciable effects of ionizing radiation on electronic equipment, and because SSF has many electronic devices located in the external environment, stringent equipment radiation hardening specifications/processes should be considered.
4. As analyses (such as the FMEAs and CILs) are completed, the ratio (20% critical items to 80% non-critical items) used in developing the environment-induced K-Factor subelement values should be revisited. This is needed because the ratio turns out to be a driving element in the value development. Also, consider requirements for non-critical equipment (e.g., 95% for critical IR, etc.)
5. Assure that the SSF Program has an effective tracking program and database so that future manned space programs will have quantifiable and traceable maintenance information for use in estimating resource demands. This data will also provide for monitoring SSF Program trends and allow personnel to be alerted to any developing adverse trend conditions. Establish possible "alarm levels" beyond which corrective action/ investigation would be required.

EVA Overhead

General Definition of Terms

EVA overhead for Space Station Freedom external maintenance refers to all extravehicular activity time that is not directly involved in the actual replacement or repair of an ORU. If a total of three hours were required to perform a one-hour worksite task, the remaining two hours would be classified as EVA overhead.

Internal tasks performed inside the pressurized volume of the Space Station (e.g., donning the extravehicular mobility unit (EMU), EMU checkout, EMU maintenance, and pre-breathing for denitrogenation do require a significant amount of crew time, and must occur prior to each EVA. However, for the purposes of this study, they are classed as intravehicular (IVA) time, and are not calculated as EVA overhead.

Background

The amount of time getting to and from a worksite, as well as the time required to set up for worksite activities, is largely dependent upon architecture and design. If the worksite is close to the starting point and if all necessary tools can be taken there in a single trip, the associated overhead is small. If the worksite is distant, and multiple trips are necessary to prepare it, the overhead will increase.

The value for EVA overhead used in our initial report was 1.7. This value was taken directly from the Cramer study on Space Station maintenance (October, 1989) and was used as a direct multiplier to the annual EVA worksite requirement.

An EVA overhead value of 1.7 means that for every hour required at the worksite, 0.7 hours would be required in worksite setup, yielding a total of 1.7 hours required for task completion.

The Cramer study overhead number was admittedly conservative, and one of the tasks of our investigation was to gain a clearer understanding of the actual EVA overhead requirement.

The demand expression for calculating the overall maintenance requirements is as follows:

Expected Maintenance Time =

$$\sum_{1}^{6}\begin{pmatrix}\text{Generic No. of}\\ \text{Failures/Class}\end{pmatrix}\begin{pmatrix}\text{K-Factor}\end{pmatrix}\begin{pmatrix}\text{Expected}\\ \text{Replacement}\\ \text{Time}\end{pmatrix}$$

Estimated by "Monte Carlo" simulation Includes effects of • # ORUs • Failure Rate • Duty Cycle	Estimated by Contractors + JSC and has the form $K = K_1 + K_2 + K_3 + K_4 + 1$	• MTTR estimated by contractors • EVA overhead estimated by JSC

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Methods

Evaluation of the EVA overhead value for Space Station required a detailed analysis of every step a crew member would make in the process of preparing the worksite for an ORU replacement. A clear knowledge of Space Station design and EVA procedures was necessary. To accomplish this task, the Mission Operations Directorate at JSC was selected. This group is responsible for planning all Space Shuttle EVA activities as well as for developing timelines and procedures for Space Station Freedom EVA activities.

Their analysis used established EVA procedures and the current Space Station design to determine an EVA overhead factor. Since it was recognized that the factor's value would be modified somewhat by the location of the worksite on the Space Station structure, two generic overhead timelines were developed. The first dealt with overhead for replacement tasks on the integrated truss assembly (ITA), the second with tasks for ORUs on the station modules themselves. The resulting values were then prorated according to the percentage of ORUs in each location, and a final generic Space Station EVA overhead factor was generated.

This value was then validated by analysis of actual flight experience with EVA on the Space Shuttle, and by the testing of EMU-suited astronauts in the weightless environment training facility at JSC.

Analysis

Extensive documentation of the EVA overhead timelines, procedures and analysis is provided in Appendix F. A very close correlation was noted between the estimates of overhead times by the Mission Operations Directorate, and the analysis of actual flight experience and engineering test runs. Detailed videotape records were compiled of applicable Space Shuttle EVA sequence, and of the weightless environment testing at JSC. Copies of these videotapes are available upon request from the Space Station Freedom Program Office at JSC.

Results

The data obtained using the Space Station Freedom design as it existed in the first quarter of 1990 resulted in an EVA overhead factor of 6.0. Strictly speaking, this means that to complete a single, one-hour task, five hours of overhead would be required in addition to the task time. More correctly, two astronauts, each performing a six-hour EVA, could perform a total of two repair tasks if each task were one hour long.

The above distinction for two astronauts is necessary because current station design requires that both EVA astronauts work together during certain portions of overhead activities. A single EVA astronaut, working alone, would not be expected to complete the single one-hour task in six hours.

Two important assumptions were made in this overhead analysis which must be taken into account if the value of 6.0 is to be viewed in its proper perspective. One is the assumption that all tasks are equal to or less than the average worksite time of 1.1 hours (actually, 25% take longer). The other is that each worksite task requires only a single EVA crew member (in fact 25% of the tasks require two). Time and resources did not permit these additional analyses, but they would clearly have increased the overhead value of 6.0 significantly. Thus the overhead value of 6.0 represents a conservative number for the current Space Station design.

The EVA overhead value of 6.0 represents the single greatest change in any parameter analyzed in this report, increasing 350% over the value cited in the Cramer study. Part of this increase is based on an evaluation of all end-to-end overhead tasks, and part is due to a complete analysis of the requirements based on current Space Station architecture. It is also a conservative value, since it intentionally did not take into account those 25% of tasks requiring greater than 1.1 hours or those tasks requiring two EVA crew members.

Since the overhead figure is a direct multiplier of the worksite time, any reduction in its value would have a profound effect on the overall maintenance requirements. It is the opinion of this task team that if all 20 of the EMTT recommendation for decreasing EVA overhead are implemented, its value could be reduced to approximately 2.5. This would have the effect of reducing the EVA requirements from 5.3 to 2.1 EVAs per week (averaged over 35 years), and from 10.4 to 4.2 EVAs per week (peak demand/year 2005). Although it is recognized that such changes would involve some architectural modifications and will have an impact on weight, volume, cost and the assembly manifest, the potential gains would seem to be overriding.

Another design goal throughout the Space Station Program should be to require that all ORUs be replaceable by a single EVA crew member or robot in 1 hour or less. This, when coupled with implementation of the 20 EVA overhead reduction recommendations, would have the effect of reducing the overhead factor to 2.0, as well as significantly decreasing the overall worksite time required.

The significant EVA requirements occurring prior to assembly completion will have a unique EVA overhead value, dependent upon Space Station architecture at the time and the possible use of the Space Shuttle as a base of operations. This new overhead value will need to be more fully understood in order to determine the maintenance requirements during the assembly phase.

It is the opinion of all those associated with the EMTT study that the Space Station Program should assign the highest priority to implementing these overhead reduction recommendations.

EVA Overhead Recommendations

1. Provide equipment necessary to allow EVA crew members to work independently in separate areas of SSF.
2. Design the CETA ORU carrying provisions to accommodate transport of multiple ORUs, eliminating the need to make more than two trips to the ULC during an EVA (one to retrieve ORUs and one to return them).
3. Design the CETA rail for direct routing to the airlock from either direction on the transverse boom without airlock spur or alpha joint switching mechanism operations.
4. Locate the CETA rail and ULCs in close proximity to one another such that use of the clothesline is not necessary.
5. Provide the capability to store and relocate the PWP components on orbit in any configuration of partial or complete assembly.
6. Design the PWP components for long-term exposure and eliminate the need to stow it in the PWS.
7. Provide the capability to stow a PWP on each CETA and a third on the Mobile Servicing System's MBS.
8. Provide the capability to stow a PWP on the MBS in such a way that it can be deployed onto the SSRMS or installed at a worksite and returned to the MBS by the SSRMS.
9. Provide for storage of one set of tools on each CETA.
10. Provide dedicated PFRs at all sites frequently visited by the EVA crew (i.e., worksite with low MTBFs).
11. Provide dual sets of dedicated PFRs at sites where crew members are likely to be working simultaneously on independent tasks (e.g., ULCs).
12. Provide spare PFRs to enable the crew to leave them in areas with high concentrations of ORUs (e.g., at each pallet), at sites which will be visited again soon, or in any location that is found to warrant a PFR.
13. Investigate potential redesigns or improvements to existing PFR sockets, wrist tethers, and other frequently used EVAS support equipment to improve operational efficiency.
14. Provide an equipment transfer device which enables:
    - Simultaneous transfer of ORUs and support equipment to/from a worksite in a single deployment
    - Efficient operation by a single, unaided EVA crew member
    - Positive control of all objects during transfer operations to prevent inadvertently "bumping" equipment
15. Minimize the number and complexity of ORU restraints required in the ULC, on the CETA, and at the installation site.
16. Investigate telerobotic applications for selected EVA overhead tasks before and after the EVA occurs to directly eliminate those tasks from the EVA timeline.

17. Provide tether points to accommodate attachment of two tethers simultaneously on all equipment which the crew must transfer, hand off, or temporarily stow using tethers.
18. Replace the CSA provided MFR and its stowage on the MBS with stowage provisions for a PWP which can accommodate unassisted deployment, installation, and stowage by the SSRMS.
19. Implement a programmatic requirement to ensure that all EVA tasks must be optimized for performance by one EVA crew member
20. Implement programmatic directions to ensure a proper balance of engineering and operational considerations to design decisions.

External Maintenance Demand Summary

Introduction

A prediction of the average amount of time spent outside of pressurized modules replacing failed ORUs was obtained by the EMTT in January 1990. This time consisted of worksite time and overhead time. The worksite time, which was predicted to be 571 hours, measures the time to remove an ORU and insert another one while at the worksite. The overhead time accounts for activities such as traveling to the ORU location, obtaining a spare, etc. When this overhead time is included, the EMTT predicted that it would take 2284 hours per year to maintain the external ORUs. Since this number was excessive, it became important to understand the component values upon which this number was based.

One of the components is the failure rate of the individual ORUs. When the EMTT examined the individual failure rate predictions from the work packages and international partners, several potential problems were noticed. First, these predictions were not derived in a consistent manner. Secondly, several ORUs which appeared to be similar in function and made of similar hardware, but designed by different groups, were associated with a wide range of failure rate predictions. Finally, the work packages and international partners provided constant failure rate predictions which at best could only average out the effects of infant mortality and limited life properties of the ORUs. In some cases, it was not apparent that infant mortality or life limits were even considered. Because of these potential problems with the failure rate values, the EMTT singled out this component of EVA time as a special area for further study. And to do this, they engaged the consultant services of Science Applications International Corporation (SAIC).

A summary of the methods SAIC used to examine the work package and international partner estimate of failure rates is discussed in the Failure Rate Findings Section of this report. A more detailed discussion is given in Appendix A.

Statement of the Problem

The average, or expected, EVA replacement time, $W(t)$, for a given ORU is

$$W(t) = E(T)E(N(t)) \tag{1}$$

where T is the time to replace that ORU and $N(t)$ is the number of failures that could occur over a period of time, t. Here the symbol "E" denotes expectation. This expression states that over some time, t, the expected amount of EVA time that would be needed to replace failures of a given ORU, is the product of the the expected number of failures of that ORU and the expected amount of time it would take to do a replacement given that a failure occurred. The total EVA expected replacement time for SSF can be computed by summing all the external ORU expected replacement times.

The expected number of failures that a given ORU can experience over time can usually be determined by first computing the failure rate for that ORU. In particular, if we let $\lambda(s)$ denote the failure rate at s, then

$$E(N(t) = \int_0^t \lambda(s)\, ds \qquad (2)$$

The form of the failure rate function, λ, depends upon the dominant failure mechanism that the ORU can experience. In some cases, these failure mechanisms operate randomly over time and can be modeled by a constant failure rate. Failures of electronic devices can often be modeled by a constant failure rate. Passive and mechanical devices, on the other hand, are often associated with failure rates that change over time. In fact, many such devices have a life time that can be reasonably well predicted. These so called limited life devices can have a failure rate that is close to zero for some period of time and then increase very rapidly beyond that period. The actual point in time where this failure occurs may not be known exactly, but in some cases may be known with high probability of being within a small range. These reasonably certain cases are generally the easiest to deal with because maintenance strategies can be scheduled well in advance of the actual failure.

When hardware is operated for the first time, there may be a high failure rate due to manufacturing imperfections. As this hardware fails and the problems are analyzed and corrected, the failure rate usually decreases to some asymptotic constant value which represents a residual rate that is due to random unexplained causes.

The problem of estimating the failure rate is related, therefore, to a problem of estimating possibly three kinds of failure rates: the infant mortality, the constant, and the limited life failure rate. This is a departure from the way failure rate was treated to obtain the January 1990 estimate. To obtain that estimate a constant failure rate was only considered. As a result, the occurrence of ORU failures was defused over time so that in any interval of time, one would expect to see about the same number of failures. When infant mortality and limited life failure are considered, the number of failures will have a tendency to bunch in time. The failures due to infant mortality will bunch in the early years, and the limited life failures will bunch in the later years.

The expected replacement time, E(T), has to account for the worksite time and the overhead time as discussed in the introduction to this section. The worksite times have been estimated by the work packages and international partners while the overhead time has been estimated by the EMTT as discussed in Appendix F.

Approach

In equation (2) the expected number of failures is expressed in terms of the failure rate function, λl. As was pointed out, this function can be expressed in terms of component failure rates that describe the failure rate during periods of infant mortality, constant failure rate, and accelerated failures due to life limits. And when a nonhomogeneous Poisson process describes these failures, the expected number of failures can be expressed as

$$E(N(t)) = \int_0^t [\ \lambda_c + \lambda_I(s) + \lambda_L(s)\ ]\, ds \qquad (3)$$

where λ_c is the constant failure rate, λ_I is the infant mortality failure rate function, and λ_L is the limited life failure rate function.

Since many of the ORUs are in the early design stages, such a refinement of the ORU failure rate into infant mortality, constant, and limited life components was not possible. Rather, SAIC chose to concentrate on six ORU classes which are electronic, electrical, electro-mechanical, structural-mechanical, mechanical, and structural. And, they chose to estimate the number of failures, rather than failure rate, in each of these six classes using a Monte Carlo simulation method. The Monte Carlo method tracks the failures of an ORU and adjusts the time to a limited life failure based on previous times to failure. This provides a more realistic model in situations where only a finite number of ORUs can fail than is the above Poisson process model.

The expected number of failures as estimated by SAIC does include the effects of duty cycle, but it does not include the effects of K-factor. K-factor is discussed in detail in Appendix D. To estimate the EVA replacement time the expected number of failures, as estimated by SAIC, was multiplied by the K-factor.

Under the assumption that the number of ORU failures is independent of the time to replace it, the station worksite time can be computed as

$$W(t) = \sum_{i=1}^{6} E(N_i(t))\, E(T_i) \qquad (4)$$

where, as in equation (1), $E(N_i(t))$ is the expected number of failures that would occur for class i and $E(T_i)$ is the expected repair time to replace an ORU from the i^{th} class.

The expected replacement time, $E(T_i)$, in equation (4) considers both the worksite time and the overhead time, and it does this in a "threshold-like" fashion according to the following algorithm. Each ORU in class i was assigned an EVA replacement time according to this algorithm. The resulting assignments were then averaged to obtain an average replacement time for class i, and this average was taken as an approximation of $E(T_i)$.

If the number of crew required to replace the ORU is 2, assign an expected replacement time of 2(MTTR + 2.5) hours.

If the number of crew required to replace the ORU is 1 and the expected worksite time is less than or equal to 1.1 hours, assign an expected replacement time of (MTTR + 5) hours.

If the number of crew required to replace the ORU is 1 and the expected worksite time is greater than 1.1 hours, assign an expected replacement time of 2(MTTR + 2.5)hours.

In this algorithm MTTR stands for the mean time to repair and, in this context, is the expected amount of time it would take to replace an ORU at the worksite. This thresholding depends on the amount of overhead time that is required to perform an EVA and the limit on how much time can be spent outside SSF. Any ORU replacement that is expected to be more than 1.1 hours of worksite time constitutes a single EVA. An ORU replacement that can be done in less than 1.1 hours, on the average, can be combined with a second ORU changeout provided the second one is also 1.1 or fewer hours. The 5 and 2.5 hours used in this algorithm are the amounts of overhead time per person that it takes to do a changeout. A more detailed explanation of overhead and worksite time can be found in Appendices C and F.

Admittedly, this is an approximation of $E(T_i)$ and does not reflect the fact that the replacement actual time, T_i, has some variance; and, it does not account for the, somewhat rare, occurrences of large worksite times. Worksite times much in excess of the 1.1 hours could extend into a second EVA day even though the algorithm would count it as one EVA. In spite of this, however, it is felt that the algorithm is a reasonable model of the expected replacement time.

Results and Discussion

Predictions of the number of failures (NOFAIL), the EVA replacement time (EVAHRS), and the number of EVAs (NOEVAS) for each year in the life of SSF are presented in that order in Table 1. The results show the effects of the staggered arrival times of the ORUs on SSF while it is being built, the effects of infant mortality, and the effects of the limited life failures of the ORUs. The numbers in Table 2, and in Figure 2, do not include the contributions of the crew return vehicle, user, and ESA since they did not provide failure rate estimates. They did, however, provide worksite time estimates and these estimates were included in the numbers that are discussed in the executive summary.

During the first year of construction, the predicted number of failures is 241 and the corresponding EVA replacement time is 1613 manhours. In the second year, 486 failures are predicted to occur, resulting in a total predicted EVA replacement time of 3240 manhours. This implies that it would take approximately 270 EVAs to just perform maintenance during this second year. And this occurs at a time when there is little or no planned capability to do maintenance. In fact even if the full maintenance capability were available, 270 EVAs would exceed the capability of a two-crew EVA team in any year. After the second year, these early large numbers of failures due to infant mortality start to wear off gradually. The biggest contributors to these early failures are the electro-mechanical ORUs.

The next large maintenance demands occur on about 11-year cycles. At year 11, the expected number of failures jumps to 874 and the corresponding EVA replacement time peaks at 5670 manhours. This projects to be about 472 EVAs, which is more EVAs than can be performed. The biggest contributor to these 11-year peaks is the structural-mechanical ORUs. As shown in Figure 2, the structural-mechanical ORU failures make up about half of the failure at these points in time and the number of failures at other points in time are much less. This implies that these ORUs could be changed out prior to almost all of their limited life failures starting at about the ninth year. The same kind of scheduled maintenance could also be planned for the structural ORUs that also fail on an 11- year cycle.

Table 2
EVA Demand Summary Over 35 Years

	YR	SM	ME	EM	ET	EE	ST	STATION
NOFAIL	1	31.10	23.65	81.90	48.33	42.28	13.92	241.18
EVAHRS	1	193.44	157.04	537.26	319.94	307.80	97.02	1612.51
NOEVAS	1	16.12	13.09	44.77	26.66	25.65	8.09	134.38
NOFAIL	2	77.75	64.50	160.16	75.18	75.50	33.06	486.15
EVAHRS	2	483.60	428.28	1050.65	497.69	549.64	230.43	3240.29
NOEVAS	2	40.30	35.69	87.55	41.47	45.80	19.20	270.02
NOFAIL	3	71.53	32.25	112.84	82.34	67.95	13.92	380.83
EVAHRS	3	444.92	214.14	740.23	545.09	494.68	97.02	2536.08
NOEVAS	3	37.08	17.84	61.69	45.42	41.22	8.09	211.34
NOFAIL	4	49.76	34.40	129.22	62.65	36.24	12.18	324.45
EVAHRS	4	309.51	228.42	847.68	414.74	263.83	84.89	2149.07
NOEVAS	4	25.79	19.03	70.64	34.56	21.99	7.07	179.09
NOFAIL	5	27.99	64.50	100.10	62.65	52.85	10.44	318.53
EVAHRS	5	174.10	428.28	656.66	414.74	384.75	72.77	2131.29
NOEVAS	5	14.51	35.69	54.72	34.56	32.06	6.06	177.61
NOFAIL	6	34.21	49.45	81.90	71.60	40.77	12.18	290.11
EVAHRS	6	212.79	328.35	537.26	473.99	296.81	84.89	1934.09
NOEVAS	6	17.73	27.36	44.77	39.50	24.73	7.07	161.17
NOFAIL	7	31.10	34.40	69.16	51.91	64.93	6.96	258.46
EVAHRS	7	193.44	228.42	453.69	343.64	472.69	48.51	1740.39
NOEVAS	7	16.12	19.03	37.81	28.64	39.39	4.04	145.03
NOFAIL	8	27.99	36.55	83.72	42.96	52.85	10.44	254.51
EVAHRS	8	174.10	242.69	549.20	284.40	384.75	72.77	1707.90
NOEVAS	8	14.51	20.22	45.77	23.70	32.06	6.06	142.33
NOFAIL	9	37.32	27.95	52.78	42.96	54.36	5.22	220.59
EVAHRS	9	232.13	185.59	346.24	284.40	395.74	36.38	1480.47
NOEVAS	9	19.34	15.47	28.85	23.70	32.98	3.03	123.37
NOFAIL	10	174.16	45.15	65.52	41.17	58.89	22.62	407.51
EVAHRS	10	1083.28	299.80	429.81	272.55	428.72	157.66	2671.81
NOEVAS	10	90.27	24.98	35.82	22.71	35.73	13.14	222.65
NOFAIL	11	475.83	66.65	98.28	64.44	69.46	99.18	873.84
EVAHRS	11	2959.66	442.56	644.72	426.59	505.67	691.28	5670.48
NOEVAS	11	246.64	36.88	53.73	35.55	42.14	57.61	472.54
NOFAIL	12	329.66	34.40	76.44	42.96	42.28	41.76	567.50
EVAHRS	12	2050.49	228.42	501.45	284.40	307.80	291.07	3663.61
NOEVAS	12	170.87	19.03	41.79	23.70	25.65	24.26	305.30

Table 2
EVA Demand Summary Over 35 Years (Continued)

NOFAIL	13	83.97	19.35	72.80	68.02	49.83	13.92	307.89
EVAHRS	13	522.29	128.48	477.57	450.29	362.76	97.02	2038.42
NOEVAS	13	43.52	10.71	39.80	37.52	30.23	8.09	169.87
NOFAIL	14	43.54	47.30	76.44	30.43	75.50	10.44	283.65
EVAHRS	14	270.82	314.07	501.45	201.45	549.64	72.77	1910.19
NOEVAS	14	22.57	26.17	41.79	16.79	45.80	6.06	159.18
NOFAIL	15	37.32	34.40	61.88	48.33	37.75	20.88	240.56
EVAHRS	15	232.13	228.42	405.93	319.94	274.82	145.53	1606.78
NOEVAS	15	19.34	19.03	33.83	26.66	22.90	12.13	133.90
NOFAIL	16	40.43	55.90	83.72	32.22	66.44	17.40	296.11
EVAHRS	16	251.47	371.18	549.20	213.30	483.68	121.28	1990.11
NOEVAS	16	20.96	30.93	45.77	17.77	40.31	10.11	165.84
NOFAIL	17	43.54	30.10	72.80	39.38	57.38	15.66	258.86
EVAHRS	17	270.82	199.86	477.57	260.70	417.73	109.15	1735.82
NOEVAS	17	22.57	16.66	39.80	21.72	34.81	9.10	144.65
NOFAIL	18	37.32	38.70	87.36	57.28	52.85	8.70	282.21
EVAHRS	18	232.13	256.97	573.08	379.19	384.75	60.64	1886.76
NOEVAS	18	19.34	21.41	47.76	31.60	32.06	5.05	157.23
NOFAIL	19	52.87	21.50	78.26	46.54	60.40	6.96	266.53
EVAHRS	19	328.85	142.76	513.39	308.09	439.71	48.51	1781.32
NOEVAS	19	27.40	11.90	42.78	25.67	36.64	4.04	148.44
NOFAIL	20	223.92	36.55	91.00	53.70	111.74	45.24	562.15
EVAHRS	20	1392.78	242.69	596.96	355.49	813.47	315.32	3716.72
NOEVAS	20	116.07	20.22	49.75	29.62	67.79	26.28	309.73
NOFAIL	21	429.18	25.80	78.26	46.54	137.41	78.30	795.49
EVAHRS	21	2669.50	171.31	513.39	308.09	1000.34	545.75	5208.39
NOEVAS	21	222.46	14.28	42.78	25.67	83.36	45.48	434.03
NOFAIL	22	286.12	36.55	54.60	51.91	90.60	46.98	566.76
EVAHRS	22	1779.67	242.69	358.18	343.64	659.57	327.45	3711.20
NOEVAS	22	148.31	20.22	29.85	28.64	54.96	27.29	309.27
NOFAIL	23	71.53	49.45	85.54	44.75	54.36	8.70	314.33
EVAHRS	23	444.92	328.35	561.14	296.24	395.74	60.64	2087.03
NOEVAS	23	37.08	27.36	46.76	24.69	32.98	5.05	173.92
NOFAIL	24	37.32	30.10	60.06	64.44	55.87	5.22	253.01
EVAHRS	24	232.13	199.86	393.99	426.59	406.73	36.38	1695.70
NOEVAS	24	19.34	16.66	32.83	35.55	33.89	3.03	141.31

Table 2
EVA Demand Summary Over 35 Years (Concluded)

NOFAIL	25	52.87	27.95	76.44	68.02	61.91	10.44	297.63
EVAHRS	25	328.85	185.59	501.45	450.29	450.70	72.77	1989.65
NOEVAS	25	27.40	15.47	41.79	37.52	37.56	6.06	165.80
NOFAIL	26	52.87	30.10	74.62	53.70	57.38	12.18	280.85
EVAHRS	26	328.85	199.86	489.51	355.49	417.73	84.89	1876.34
NOEVAS	26	27.40	16.66	40.79	29.62	34.81	7.07	156.36
NOFAIL	27	49.76	34.40	89.18	39.38	73.99	13.92	300.63
EVAHRS	27	309.51	228.42	585.02	260.70	538.65	97.02	2019.31
NOEVAS	27	25.79	19.03	48.75	21.72	44.89	8.09	168.28
NOFAIL	28	52.87	23.65	70.98	35.80	63.42	6.96	253.68
EVAHRS	28	328.85	157.04	465.63	237.00	461.70	48.51	1698.72
NOEVAS	28	27.40	13.09	38.80	19.75	38.47	4.04	141.56
NOFAIL	29	74.64	21.50	103.74	41.17	48.32	8.70	298.07
EVAHRS	29	464.26	142.76	680.53	272.55	351.77	60.64	1972.51
NOEVAS	29	38.69	11.90	56.71	22.71	29.31	5.05	164.38
NOFAIL	30	217.70	32.25	87.36	44.75	63.42	38.28	483.76
EVAHRS	30	1354.09	214.14	573.08	296.24	461.70	266.81	3166.07
NOEVAS	30	112.84	17.84	47.76	24.69	38.47	22.23	263.84
NOFAIL	31	438.51	58.05	100.10	32.22	60.40	92.22	781.50
EVAHRS	31	2727.53	385.45	656.66	213.30	439.71	642.77	5065.42
NOEVAS	31	227.29	32.12	54.72	17.77	36.64	53.56	422.12
NOFAIL	32	239.47	27.95	83.72	39.38	57.38	43.50	491.40
EVAHRS	32	1489.50	185.59	549.20	260.70	417.73	303.19	3205.91
NOEVAS	32	124.13	15.47	45.77	21.72	34.81	25.27	267.16
NOFAIL	33	87.08	40.85	85.54	46.54	63.42	10.44	333.87
EVAHRS	33	541.64	271.24	561.14	308.09	461.70	72.77	2216.58
NOEVAS	33	45.14	22.60	46.76	25.67	38.47	6.06	184.72
NOFAIL	34	65.31	40.85	70.98	42.96	58.89	10.44	289.43
EVAHRS	34	406.23	271.24	465.63	284.40	428.72	72.77	1928.98
NOEVAS	34	33.85	22.60	38.80	23.70	35.73	6.06	160.75
NOFAIL	35	52.87	23.65	85.54	39.38	70.97	13.92	286.33
EVAHRS	35	328.85	157.04	561.14	260.70	516.66	97.02	1921.41
NOEVAS	35	27.40	13.09	46.76	21.72	43.06	8.09	160.12

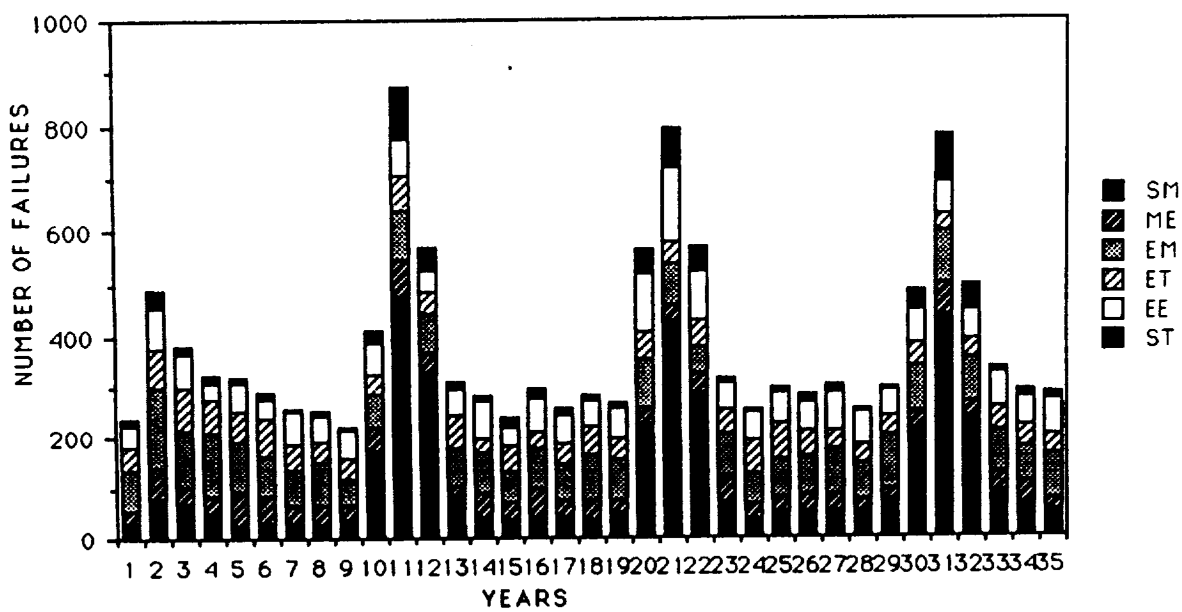


Figure 2. Failure Profile

Recommendations

As a result of this investigation, a number of recommendations related to SSF maintenance demands on the station are suggested.

1. The project should develop a comprehensive maintainability model that should be used to:
   a. Project maintenance demands as the design of SSF matures
   b. Project the logistics and spares inventory that would be required to support proposed design options
   c. Establish requirements on the types of measurements that SSF should log as it begins operation.

This model should be part of a more comprehensive supportability model that can be used to gage design trade-offs in terms of the SSF life cycle cost and performance variables. It is important that these models be developed early in the program to establish the need for the kinds data that should be collected to be able to predict future maintenance and logistics demands. In the past NASA has not collected, for example, failure histories in an easily accessible fashion that would allow reliability growth estimates to be made in a routine way. In part, this has greatly complicated the ability to do reliability studies on major programs such as Shuttle.

2. For the current SSF design projections of maintenance demand imply that the station will experience a large number of failures as it is being built. This implies that a logistics plan should be one of the first design concepts that should be developed. Provisions for sparing, resupply, and maintenance should be in place before any major construction phases are begun. It may be that by starting the station design with a logistics concept, a different construction sequence or even a different approach to construction will emerge.
3. The design of SSF should include a graceful degradation policy that will dictate the way the station should cut back on its performance as failures accumulate and are not immediately repaired. This degradation policy should view the station as a facility that can perform at less than full capacity a substantial part of its life.
4. Since SSF is projected to have some large periodic maintenance demands due to limited life failures, consideration should be given to a dry- dock concept in which periods are set aside to perform a station overhaul with a maintenance crew that is larger than the crew that permanently mans the station.
5. Commonality of parts should be stressed as much as possible in constructing ORUs. For those ORUs whose dominant failure mode is due to random causes, such as electronic ORUs, consideration should be given to a sub-ORU concept in which parts of the ORU could be repaired at the station rather than requiring that the entire ORU be brought back for refurbishment on the ground. Establishing commonality at this lower component level should be easier and greatly reduce the amount of weight that needs to be transferred between the ground and orbit. If the ORUs are built in a more modular way, such on orbit repair could possibly be done inside pressurized modules.
6. Since SSF is being viewed as a stepping stone toward the manned exploration of the planets, it should be a facility in which we learn to do things that will be needed later. In particular, this report points out that maintainability is an important concept in the overall design process. There are, however, many unique problems that have yet to be solved in reliability and maintenance of remote facilities. Much of the research and development in this area has been sponsored by the DOD and the nuclear industry; but, there are problems that are unique to space vehicles. NASA should consider, perhaps jointly with DOD and the nuclear industry, sponsoring research in this area. The results of this research should be tested on the Space Station.

Comments

It is very difficult to accurately determine the failure rate of a device that has not been built and tested or even gone through a detailed design. Such is the case with SSF ORUs that are being considered in this analysis. The point estimates that have been derived for the number of failures, mean time between maintenance actions, and EVA time will have an element of uncertainty; and,the uncertainty may be substantial. Without further study, it was decided that we would not attempt to quantify the uncertainty. Never-the-less, the reader should be aware of this. Based on comparisons with other systems, the numbers that have been derived are, however, reasonable approximations if one only considers the average maintenance loads over a period of time of about 10 years. The 10 years being the approximate amount of time for which data on these other systems (i.e., satellites, Shuttle, etc.) have been collected.

Part of the uncertainty is related to the timing with which failures may occur. Non-electronic systems typically do not fail with just constant failure rate over time; rather, they fail in cycles that correspond to the influence of various wear-out mechanisms. In this study there was an attempt to understand the life limits due to wear-out, however, there may still be considerably uncertainty relative to the magnitude of the constant-failure-type of failures and the limited life failures. In other words, it is not clear to what extent the failures will be defused over time as opposed to occuring in bunches over time.

Acknowledgments

We would like to acknowledge the efforts of SAIC in providing the failure estimates that were used in this analysis and to acknowledge Robert Graber and Linda Doran of Ford Aerospace for providing the analysis results.

Assessment of Space Station Freedom Robots in the Performance of Maintenance

Objective of the Evaluation

The objective of this study was to evaluate the effectiveness of the Space Station Freedom (SSF) robots in the performance of external maintenance and determine the associated reduction in EVA required.

Evaluation Approach Used

The EMTT held detailed discussions with the designers of the SSF robots to determine the baseline capabilities of the robots and any high potential additional features that would improve the robots performance of maintenance tasks. While ORU replacements were the primary maintenance tasks evaluated, the performance of inspection by the robots was also investigated.

An assessment was made of the general awareness in the ORU design community across the SSF Program of the capabilities of the robots to perform maintenance and the degree to which the current designs had been made to be robot compatible. A robot (and EVA) compatible "box-type" ORU was designed, reviewed by representatives of the SSF work packages and international partners, and fabricated as a mockup. This mockup was tested both for robot compatibility in the JSC robotics laboratories as well as for EVA compatibility in the Weightless Environment Test Facility.

The SSF robots were evaluated for effectiveness in supporting the setup and takedown of the EVA worksite equipment. Examination was also made of the advantages offered by adding ground-based remote control of the SSF robots to perform maintenance tasks.

A major effort was accomplished in expanding the ongoing robot performance computer simulations to evaluate 16 representative ORU maintenance tasks to determine the feasibility of accomplishing these tasks and also to determine end to end timelines of the entire task scenarios.

A synthesis of all these parallel efforts was made to determine the "robot discount effect" on maintenance EVA required. The crew time overhead of operating the robots from inside the SSF was also determined. Finally, a list of recommendations was compiled.

Further details of this evaluation are found in Appendix H.

The Space Station Freedom Robots

The SSF robot team consists of five major contributions of robotic devices from three countries. These robots offer a wide variety of both common and unique capabilities. All robots will be electrically powered servo-stabilized articulated mechanisms that can be controlled by the astronauts from inside the Space Station. All will be instrumented and interfaced to the on-board data management system to provide data for monitoring by the crew and ground controllers. All will have computational capabilities to support complex control algorithms. All of the devices will carry their own television cameras. Four of the devices will be transportable about SSF to be able to perform work throughout. Four of the devices will be designed to accommodate upgrades in robotics technologies. None of these robots will be free flying. A fundamental figure of merit for robots is the number of "degrees of freedom" they possess which is the number of active joints that can be commanded for motion. For reference, the Space Shuttle Remote Manipulator, the only operational space robot, has six joints (degrees of freedom).

The U.S. will provide the Mobile Transporter (MT) which is the robotic transportation mechanism for SSF. The MT will be capable of movement along and around the outside faces of the five-meter truss bays. The MT will provide positive latching on four node pins at all times through eight latching mechanisms and will have dual electronics and drives for failure tolerance. It will be battery powered during transit and rechargeable at power data grapple fixtures located along the truss. The MT will have two articulated arms that will be used for positioning the EVA astronauts during the performance of maintenance similar to the way the Shuttle RMS is used to position the EVA crews. The MT will be used to transport the Flight Telerobotic Servicer (FTS) and the Canadian-provided robots to the worksites. The MT will have 13 degrees of freedom.

The U.S. will also provide the FTS which will be a two-armed robot with a stabilizing leg that will be capable of dexterous manipulation in both free space (movement) and constrained space (force application). The FTS will be able to be moved to and left at a worksite to perform maintenance tasks either while plugged into a power fixture or on self-contained batteries. The FTS will have about a 15-foot reach when fully extended and will have television cameras on each arm and 2 cameras on its head. The FTS will carry in a tool holster tools that can be interchanged on the end of its arms. The FTS will have the unique capability to provide back to the crew operator the "feel" of when contact is made by the robot's arms with structure in the workspace. This "force reflection" will be of great advantage in performing delicate tasks. The FTS will have 19 degrees of freedom.

Canada will provide a 57-seven foot long second generation space manipulator based on the highly successful Shuttle Remote Manipulator System. The Space Station Remote Manipulator System (SSRMS) will be a mirror image design about its elbow joint and will be able to be operated with either end as its base (and the opposite end grasping the payload). It will thus be able to operate from either the parked MT or from power data grapple fixtures strategically located about the station. It will be able to "walk like an inchworm" from grapple fixture to grapple fixture to places unreachable by the MT. (This capability is called "pedipulation.") The SSRMS will have dual electronics and drives for failure tolerance and will provide local mobility for the smaller robots and EVA crew at the worksites. The SSRMS will have seven degrees of freedom.

Canada will also provide the Special Purpose Dexterous Manipulator (SPDM) that will have two arms and a hinged body with a reach of about 25 feet when fully extended. The SPDM will operate from the end of the SSRMS, from the base of the MT or from the power data grapple fixtures. It will have dual electronics, cameras on each arm and on its head, and will have interchangeable tools for the ends of its arms. The SPDM has 19 degrees of freedom.

Japan will provide a Large Main Arm robot on the Japanese Experiments Module with the capability of picking up both experiment payloads. They will also provide a Small Fine Arm for dexterous payload tasks. These arms will have a combined reach of about 25 feet. Currently, the Japanese arms are used only for changeout of Japanese payloads and do not contribute to SSF maintenance. Moreover, neither these payloads nor the Japanese ORUs are compatible with the other SSF robots. The Japanese robots together have a total of 14 degrees of freedom.

The Utility of the SSF Robots

The SSF robots have been found to be a worthwhile resource with the potential of performing a majority of the ORU replacements required, provided that the ORUs are properly designed to be compatible with the robots. Among the design requirements to make the ORUs robot compatible are the following:

1. The ORU must have geometric targets to aid in the positioning of the robot attachment tools and the positioning of the grasped ORU itself.
2. The ORU must have a handle to allow rigid gripping with a simple, drivable fastening and release mechanism with torque reaction capacity.
3. The ORU must have straight in and straight out insertion and removal movement.
4. The ORU must have enough stiffness not to deform during insertion, removal, and transport.
5. The receptacle of the ORU must have tapered alignment guides to aid the ORU insertion and removal.
6. The ORU must have a size and shape that permits its transport into and out of the worksite.
7. The ORU must have straightforward accessibility.

The SSF robots have also been found capable of performing all inspections that cannot be performed using the truss-mounted television cameras. There is no need to dedicate any EVA solely for the purpose of inspections.

The Performance of SSF Robots

For robot-compatible ORUs, the SSF robots have been found to perform in terms of crew hours as well as or better than EVA using the design baseline EVA equipment when performing similar tasks. Addition to the robots of more automatic features would dramatically reduce the crew time required. The particular automatic features that are most beneficial in reducing crew time are on-board collision avoidance and the ground-based remote control of the robots. For robot-difficult ORUs, automatic features will still aid in reducing the crew operator time, but the difficult ORUs will always require more crew time than that required by the robot-compatible ORUs.

The Availability of the SSF Robots

The MT and the FTS will be on board the SSF from first element launch (1995). The SSRMS will arrive on the fourth launch (1995) and the SPDM will be delivered on the eighth launch (1996). All baseline design capabilities will be available at orbit deploy, and all robots are fault tolerant. However, the failure rate assessment by the EMTT has determined that the robots, as a group, will include about 15 to 18% of the overall failures. Downtime for repair of the robots must be accounted for in the operation planning of timelines and spares logistics.

Operational use of the automatic features should occur as confidence in the robots accrues and as needed to reduce the crew time. It is the opinion of the EMTT that this operational use of automatic features should begin no later than one year after orbital deployment.

Verification of the SSF Robots

The SSF robots are as complex as any space system that is flown. It is mandatory that rigorous preflight testing and system verification be performed on the robots prior to their use. This is especially true of the automatic features. This verification requires multiple levels of testing at multiple facilities by multiple organizations and represents a significant level of both technical and management effort. Furthermore, it is very difficult to test a zero-g space robot in the one-g Earth environment. Compromises in physical test articles are inevitable and simulation models often become problematical. Interpretation of these test results also is very difficult. However, this verification is no more difficult than that undertaken and achieved for the Space Shuttle flight control system, and it is felt that there is no technical reason why the proper verification of the SSF robots cannot be achieved.

The Status of Robot-Compatible ORUs

An assessment of the SSF Program regarding the awareness of the ORU designers of the utility, performance, and interface requirements of the SSF robots revealed that while a certain amount of very good design progress has been achieved, much more remains to be done. Canada and NASA LeRC Work Package 4 have had the longest ongoing efforts at designing robot-compatible ORUs and currently are reporting that 67% and 82% of their ORUs, respectively, can be considered robot compatible. Work Package 3 ORUs, though small in number are all compatible. The User payloads will be required to be robot compatible.

The FTS designers have been recently concentrating on making the FTS ORUs compatible with 100% being the target goal. Work Package 2 has the most ORUs and has only begun a process to evaluate their ORUs for robot compatibility. Work Package 1 requested robot characteristics at the EMTT midterm meeting.

The Criticality of Making ORUs Robot and EVA Compatible

The successful performance of maintenance ORU replacement by the robots (and the EVA crew) is enabled by the successful design of the ORUs to be compatible and accessible. The SSF currently does not have design standards for this purpose for robot interfaces, and the EVA standards in place are at such a high level that no assurance can be assumed that this critical compatibility will be achieved.

At the EMTT midterm meeting, a working group that included ORU designers for all work packages, the robot designers, and the EVA system designers agreed upon 19 relevant design parameters for a "box type" ORU and designed such a representative box. This design was mocked-up and tested in the JSC robotics laboratories and in the Weightless Environment Test Facility. These tests showed that an ORU can be designed to be both robot- and EVA-compatible without significant weight or other penalties and that such an ORU can be easily installed and removed by either a robot or EVA.

Admittedly, there are some ORUs that are very difficult to make robot- and EVA-compatible. Such items as thermal blankets, cables, "buried" mechanisms, mechanism housings, and fluid lines are problematical in this respect. Nonetheless, if an item cannot be assured to last for the entire lifetime of the SSF, it must be designed to be replaced. Since this is such a critical point, the EMTT recommends that

> For those components that cannot be assured to last for the 30- year life of SSF, that the designers be challenged to produce 75% of all ORUs to be replaceable by robot or EVA crew in less than one hour after the arrival of the maintenance agent at the worksite and that the remaining 25% be replaceable in less than three worksite hours.

Robot Support of EVA

The SSF robots can support EVA in two ways. Prior to and after EVA, the robots can perform worksite setup and takedown, respectively. This involves the installation and removal of the portable foot restraint and stanchion at the worksites for a clocktime savings of 36 minutes per worksite. The worksite tools, of course, must be designed to be robot compatible.

The robots also can support the crew during EVA by providing crew mobility in the foot restraints on the end of the SSRMS and the MT astronaut positioning arms. This technique has been proven very productive on Shuttle missions. The robots can also provide ORU and tool mobility as well. Interactive handoff between EVA crew and robot of tools and equipment is within the capabilities of the SSF robots, but the definition and evaluation of such procedures requires the availability of sophisticated simulators and test facilities that are still in development.

Automatic Capabilities of the SSF Robots

Included in the baseline design of the SSF are the automatic robot features that provide automatic self test and checkout, mobile transport across the truss bay faces, stored trajectory motion of the robot arms, and machine vision for the SPDM. These automatic features have resulted in the baseline robot capability of requiring less crew time than that required by EVA to perform compatible ORU changeout.

The addition of on board collision avoidance (for the motion of the robot arms) would reduce the maintenance task clock time and greatly reduce the crew time required. In support of the initialization of the collision-avoidance process, the provision of a ground-based electronic representation of the SSF geometry would also be required. This geometry database is referred to as a "world model" in that it defines the "world" in which the robots operate. Such a model could also be used to drive the reference geometry required for the ground-based simulators and crew trainers that also require such information but, to date, have not used a common electronic source.

Ground Control of SSF Robots

Ground control of the SSF robots is not in the Program baseline, but if added, would result in significant reduction of crew time required to perform maintenance. Addition of ground control would require that collision avoidance also be added to the SSF robot design. The ground-to-orbit communication links in the SSF baseline are adequate to support uplink commands to the robots and downlinked data and video for monitoring of the performance of the robots.

A minimum communications lag of about 2.7 seconds round trip exists that must be taken into account when designing the use of the robots. In general, a "command and wait process" is required to be used meaning that a command signal would be sent from the ground to invoke an automatic sequence on board and that the ground controllers would necessarily wait for at least 2.7 seconds to receive a confirmation that the command had been received by the robot to start the automatic sequence. The sequence would then proceed until either the task were successfully completed or an out-of-tolerance condition were encountered that required the sequence to cease. This automatic sequence would be fail-safe and self-limiting.

Robot Maintenance Task Timeline Analysis

An evaluation was made of 16 representative robot-compatible ORU changeout tasks using JSC robotics simulators that modeled robot dimensions, joint travel and rates, ORU dimensions and locations, geometries of other equipment in the worksite, camera views from the robots and truss cameras, and detailed scripts for each task. Each task was examined in detail for robot reach and clearance of all motions to remove and install each of the ORUs at the worksite under the control of a human operator. The time required for each task was recorded as well.

Fourteen other steps in the end-to-end timeline of robotic performance of maintenance were identified and evaluated. The values used for these steps were based on simulation, specification values, or similarity comparison. The interaction of the robot with the yet undefined logistics carrier was identified as potentially as significant as the worksite task itself. The logistics carrier will provide the storehouse for the spare ORUs and serve as the receptacle for the replaced ORUs. Removal and installation of ORUs with respect to the logistics carrier may prove more difficult than worksite installation and removal due to the more stringent ORU fastening required for launch and landing loads and vibration. It is critical that the logistics carrier be designed to be robot and EVA compatible.

Conversion of Robot Task Time to IVA Crew Hours

An integrated assessment of the end-to-end timelines of the 16 ORU replacement scenarios, the distribution of the locations of the ORUs on the Space Station, and the robotic automatic features in the baseline SSF design was made and a representative serial robot task timeline was synthesized. This typical timeline represents what might reasonably be expected for the time required to conduct an ORU changeout by the time of Assembly Complete (1999) using verified and operationally mature robots.

The conversion of the robot timeline to onboard crew member hours required during manual control assumed a full time crew to operate the robots during all periods of power on. This control mode is called "Teleoperation" and is the technique by which the Shuttle RMS is operated. The Shuttle flight rules also require a second crew in fulltime support of the RMS operator to assure collisions are avoided, to perform camera view switching, and to read out checklists.

For automatic control modes, the assumption was made that the crew member's attention was required only 20% of the time the robot was performing an automatic task. This 20% value is allowed for the crew to issue proceed commands or to resolve caution and warning advisories that would be automatically displayed by the robot's automatic control system.

These estimates are summarized in the following table.

The Teleoperations Only column shows the hours required for the robots to be powered on to perform the maintenance task.

The Baseline SSF Robot Capability column lists the crew-member hours required to be committed to the performance of the task under the current SSF design capabilities.

The Baseline with Collision Avoidance Added column lists the crew-member hours required to perform the task if onboard collision avoidance were added to the current design.

The Baseline with Collision Avoidance and Ground Control column shows the crew-member hours required to perform the task if both these features are added to the current design.

The values in parentheses are for robot-difficult ORUs, meaning that four hours at the worksite are required to remove and replace the difficult ORU. The other values are for a robot-compatible ORU, meaning only one hour is required at the worksite for replacement, or that the values are independent of the nature of the ORU (such as robot self test and checkout).

If the assumption is made that two crew members are required for these operations, the bottom line values should be used. While a two-member rule is probably valid for the more difficult steps such as robot positioning and ORU replacement under teleoperated control, two members are probably not required for self test, transport, or for any of the steps performed automatically.

Estimation of Total Crew Time Required for Maintenance Including the Use of Robots After-PMC

Because the design of the SSF ORUs is not yet mature, the overall performance of the use of robots to perform SSF maintenance can only be done in a parametric sense. This means that assumptions must be made regarding the degree with which the ORUs can be made robot compatible.

Total Operator Time for One Typical Robot Task for Robot-Compatible (and Robot-Difficult) ORU Replacement (All Time in Man-Hours)

	Teleoperations Only		Baseline SSF Robot Capability		Baseline With Collision Avoidance Added		Baseline With Collision Avoidance and Ground Control Added	
Self Test, Checkout of Robots	4.5		0.9		0.9		0	
Transport Robots, ORUs Tools	2		0.4		0.4		0	
On/Off Load Robots, ORUs, Tools	3	(5)	3	(5)	0.6	(3.8)	0	(3.5)
Positioning Robots at Worksite	0.5	(3.5)	0.5	(3.5)	0.1	(0.7)	0	(0)
Remove and Replace ORU	1	(4)	1	(4)	0.2	(4)	0	(4)
Total Time for 1 Crew	11	(19)	5.8	(13.8)	2.2	(9.8)	0	(7.5)
Total Time for 2 Crew	22	(38)	11.6	(27.6)	4.4	(19.6)	0	(15)

Four scenarios were generated that assumed all combinations of the SSF baseline EVA support equipment performance, performance of EVA with improved support equipment, robot-compatible ORUs, and robot-difficult ORUs.

The scenarios also used the ORU failure profiles generated using the SAIC Monte Carlo simulation, the derived values of K factor, the best estimates of EVA worksite time, and the EVA overhead task performance considerations. The scenarios also assumed that one EVA was conducted every two weeks of the year whenever the Shuttle was not present at the SSF, and that for the five times a year that the Shuttle was present, a total additional 11 EVAs were performed. Thus, an annual total of 34 EVAs were assumed to perform maintenance for a total of 1,241 man-hours per year expenditure.

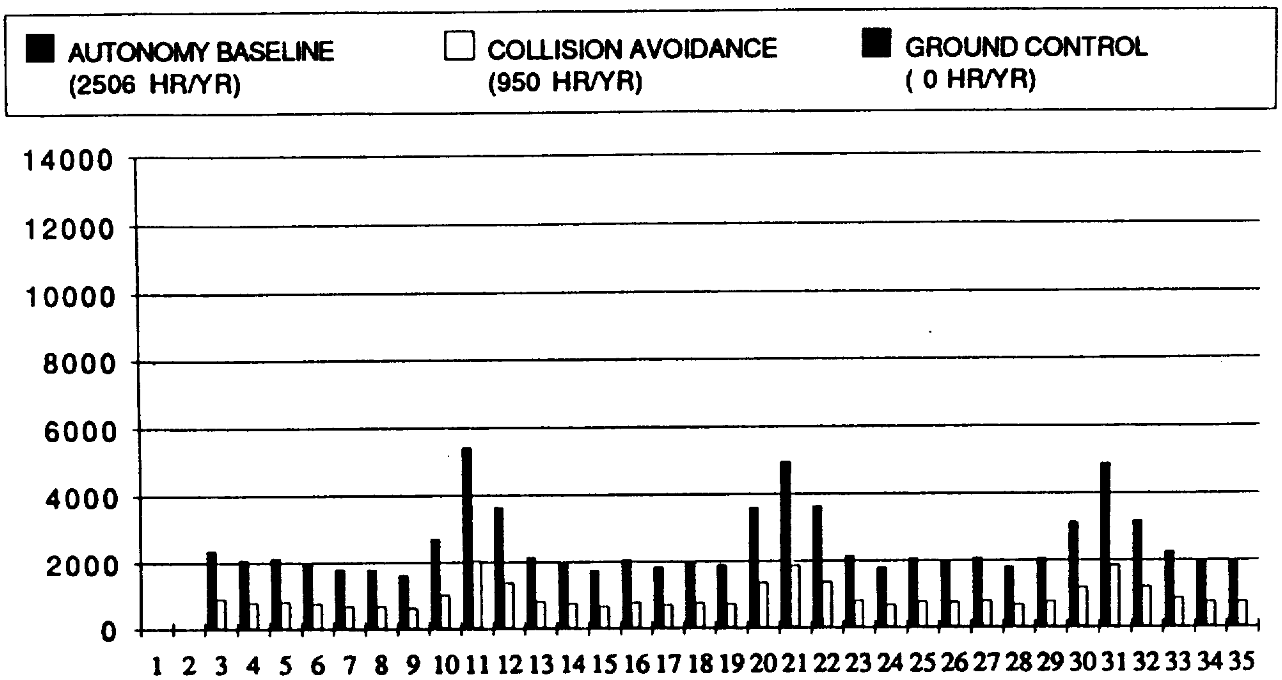
Given the 34 EVAs per year, the difference of the maintenance (ORU replacement) required and the maintenance that can be accomplished during these 34 EVAs is the *maintenance shortfall* that must be accomplished by the robots. The EVA performance is dependent upon the design of the EVA support equipment and approximates two ORU replacements per EVA using the baseline EVA equipment and potentially six ORU replacements per EVA if all the EMTT recommended changes to the EVA equipment are incorporated into the SSF baseline. Maintenance shortfalls were determined for both the baseline EVA performance and for the improved EVA equipment performance and were found to represent 86% and 59% of the required maintenance, respectively.

For each shortfall profile for the years 1997 to 2031, the intravehicular activity (IVA) crew time required to operate the robots was determined for performing the maintenance shortfall. This evaluation was made for the baseline SSF robot design capabilities, for the baseline with collision avoidance, and for the baseline with both collision avoidance and ground control capabilities added. The resulting profiles of crew time required to operate Space Station Freedom robots to complete the mainentance shortfall for the four scenarios are found in the following four bar graphs. These values are for one crew member's time only. To the annual values of crew time in each graph must be added the annual EVA crew time of 1241 hours to determine the total annual external maintenance required. Dramatic decreases in crew hours required were found with the assumed incorporations of these additional automatic features to the robot systems.

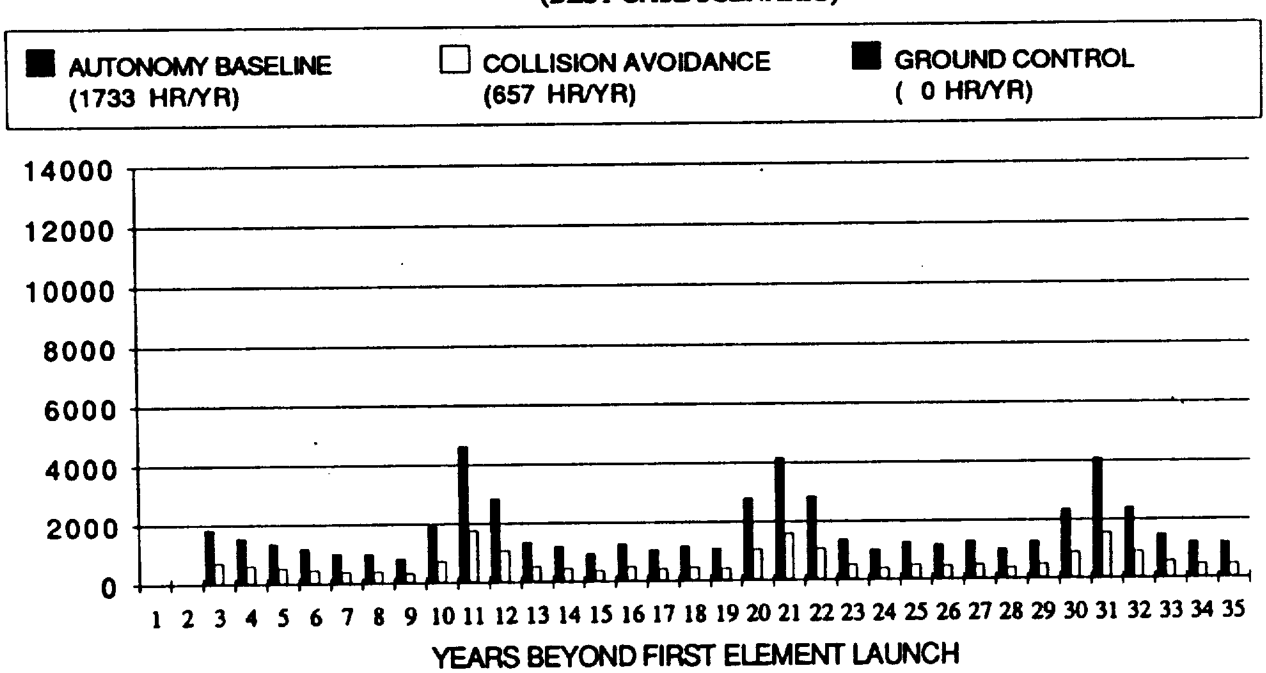
For the baseline SSF design, assuming that the ORUs that contribute 86% of the maintenance requirements can be made robot compatible, the average annual crew time required to perform this maintenance with the robots and to perform 34 EVAs to accomplish the remaining maintenance is a total of 3747 man-hours per year (2506 for robots/Reference Scenario 1241 for EVA). By incorporating all EMTT recommended changes to the EVA equipment, adding robot on board collision avoidance and ground control, and designing the ORUs that contribute to 59% of the maintenance demand to be robot compatible, the crew time per year can be reduced to 1241 (all EVA) hours per year.

The bar graphs of IVA crew time for robot-difficult ORUs clearly indicate the operational penalty associated with not designing the ORUs for maintenance. The annual average values range from 5963 to 2241 hours per year to each of which must be added the EVA value of 1241 hours per year.

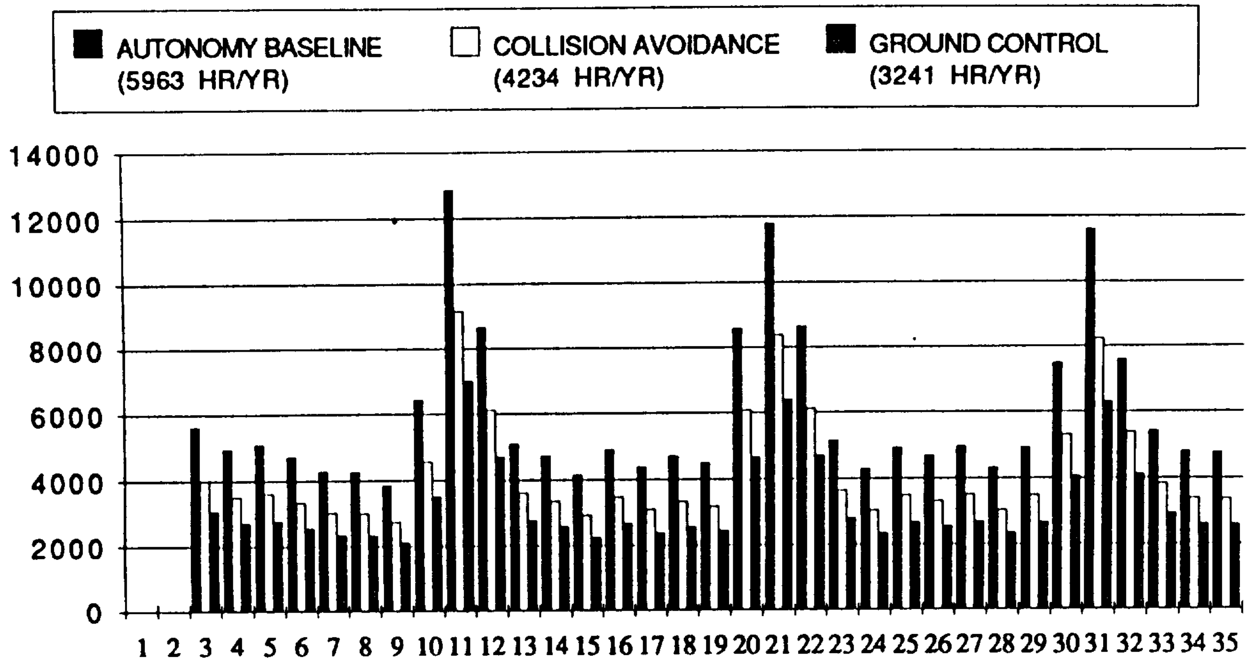
IVA CREW TIME FOR ROBOTIC PERFORMANCE OF MAINTENANCE SHORTFALL
WITH BASELINE EVAS AND ROBOT-COMPATIBLE ORUs
(REFERENCE SCENARIO)



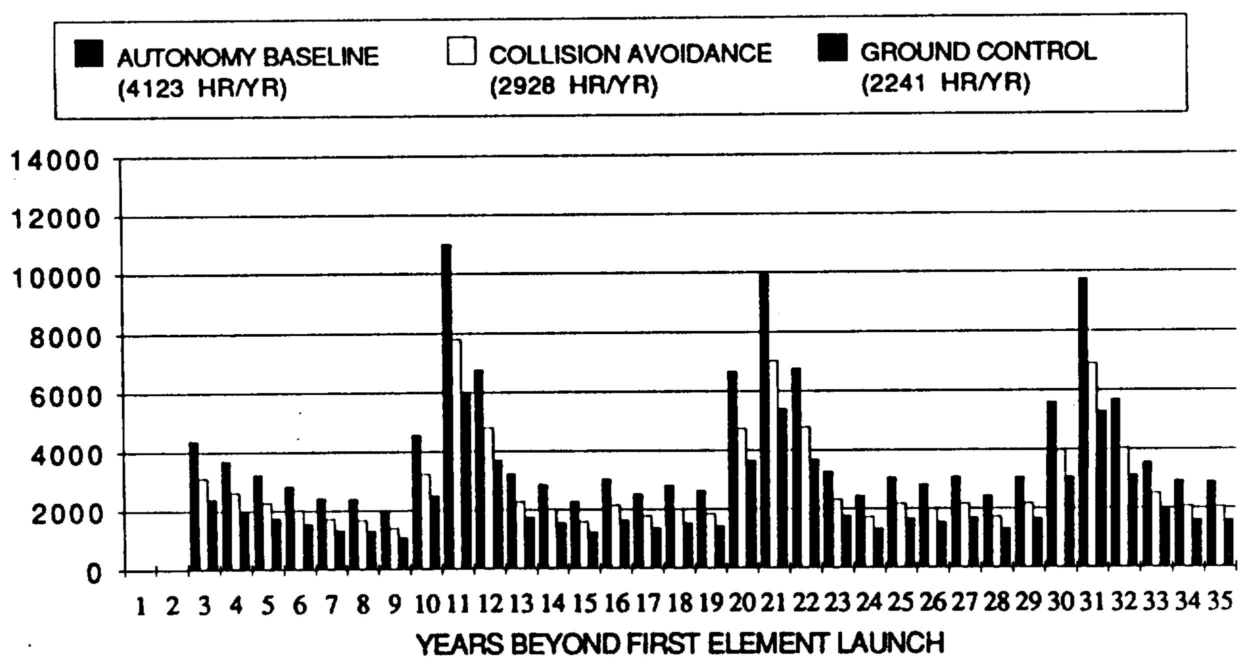
IVA CREW TIME FOR ROBOTIC PERFORMANCE OF MAINTENANCE SHORTFALL
WITH IMPROVED EVAS AND ROBOT-COMPATIBLE ORUs
(BEST CASE SCENARIO)



IVA CREW TIME FOR ROBOTIC PERFORMANCE OF MAINTENANCE SHORTFALL
WITH BASELINE EVAS AND ROBOT-DIFFICULT ORUs
(WORST CASE SCENARIO)



IVA CREW TIME FOR ROBOTIC PERFORMANCE OF MAINTENANCE SHORTFALL
WITH IMPROVED EVAS AND ROBOT-DIFFICULT ORUs
(NEAR WORST CASE SCENARIO)



Feasibility of Using the Robots for Maintenance During Assembly Phase

While the use of the SSF robots to perform maintenance after the permanent manned capability phase has been determined to be potentially quite effective, the use of robots to perform maintenance during SSF assembly is more problematical. Robots perform best in a well-structured environment, and the assembly phase will produce a changing SSF configuration as it is put together. The robots can still be used to perform maintenance during this phase, but their productivity will be less due to the changing workspace environment and the associated variations in crew procedures required to operate in this changing environment..

The nominal (assuming no failures) assembly sequence has been under study for a long time to determine what can and cannot be done with the SSF robots to assist in assembly. The EMTT robot analysis approach was the first integrated look at applying robots to performing maintenance tasks and concentrated on the Assembly Complete SSF configuration. Robot performance of maintenance during assembly should now be assessed based on the processes begun by the EMTT and integrated with the nominal assembly analyses.

The FTS and the MT will be on board SSF from the first flight in 1995; the SSRMS will also be on board in 1995 and the SPDM in 1996. With Permanent Manned Capability occurring in 1997, there will be about two years of permanent robot presence on SSF prior to a permanent manned presence. Advantage could be made of this availability of the robots to perform maintenance in between Shuttle visits by the addition of collision avoidance and ground control of the robots to the SSF Program and an aggressive early use of these features. This approach would have an associated technical risk because of the expanded scope of design effort required to accommodate the assembly workspace variations. Furthermore, the verification process required for reliance on these ground-controlled automatic features would be intensive and would include an associated schedule risk.

The SSF robots will be able to contribute to performing some of the maintenance required during the assembly phase, but to accomplish a majority of the maintenance required could require an aggressive use of automatic features that must be added to the baseline SSF robot capabilities.

SSF ROBOTICS CONCLUDING REMARKS

The SSF robots have been found to provide a worthwhile resource capable of assuming most of the external maintenance workload by assembly complete. The performance of the robots for external maintenance is enabled through robot-compatible ORU design. An 80% goal of robot-compatible ORUs is recommended, but can only be achieved through the establishment of associated design standards and the enforcement of these standards.

The SSF robots should be further integrated regarding the performance of maintenance among the robots themselves. All robots should be capable of being repaired to the greatest extent possible by some combination of the other robots without the use of EVA. The design standards for robot-compatible ORUs should be applied to the robots' ORUs.

With the current Space Station baseline design, crew time commitment for maintenance using the robots is comparable or better than the EVA crew time conducting the same maintenance tasks. Robot and crew performance are greatly enhanced by the addition of on-board collision avoidance and remote control of the robots from the ground. An aggressive early use of these features should be considered for performing maintenance during the Space Station assembly phase in between Shuttle visits.

The SSF robots are highly complex, but are no more complex than previously flown space systems. Rigorous verification of the robotic hardware and software is mandatory and should be patterned after the successful verification practices used for the Shuttle flight control systems.

Robotics Recommendations

1. Rely on SSF robots to accomplish a majority of the external maintenance workload by Assembly Complete.
2. Define, adopt, and enforce program-wide ORU/robot compatibility design standards.
3. Define, adopt, and enforce program-wide ORU worksite accessibility standards.
4. Implement an on-board collision avoidance capability in the Mobile Service System.
5. Implement a ground-based SSF geometry electronic database ("world model") for uplink initialization of on-board local robot workspace geometries and collision avoidance algorithms.
6. Implement ground-based remote control of SSF robots for monitoring and control of all robot automatic functions.
7. Implement a rigorous verification program for all robotic functions with special emphasis on all automatic functions.
8. Implement a "robot repair of robots" policy to ensure that maximum utility of robots is achieved with a minimum of EVA expenditure.
9. Integrate the use of all SSF robots (the US Mobile Transporter, the US Flight Telerobotic Servicer, the Canadian Mobile Servicing Center and Special Purpose Dexterous Manipulator, and the Japanese Large Arm and Small Fine Arm) both as maintenance agents and as receivers of maintenance.
10. Begin analyses of SSF robots (as a group) performing multiple serial and multiple concurrent tasks for the purpose of optimizing robot and crew efficiencies.
11. Begin analyses of the use of the teaming of SSF individual robots and sets of robots with EVA astronauts for the performance of maintenance tasks to optimize the efficiencies of the combined set of human and machine maintenance agents.
12. Evaluate the benefits of the use of ground-controlled robots early in the assembly time period in between Shuttle flights to accomplish the maintenance tasks required.
13. Perform all inspections of exterior surfaces through an optimized combination of truss-mounted closed circuit television cameras, the SSF robot cameras, and the use of the SSF robots to position any additional inspection sensors identified in the future.
14. Design all EVA equipment to be robot-compatible ORUs to facilitate robotic assistance prior to, during, and after periods of EVA.

Other Considerations

Influence of the Spares Inventory on Maintenance

Before a failed ORU can be replaced, a spare must be available. This simple fact can be a major determinant of any maintenance strategy. The consequences of the size of the spares inventory and the frequency with which resupply is needed must be compared with the other logistical demands of the Space Station. It may be that with the current design, the logistics needs related to the spares inventory are prohibitive if the station is to stay in repair without letting the performance appreciably degrade. Based on our current understanding of the number and frequency of random failures, a spares inventory of approximately 100 ORUs resupplied every 90 days would be needed just to take care of the ORU types that fail most frequently. Spares for the others would not be kept on board, but would have to be supplied when a Shuttle arrives. Such a strategy for providing spares may or may not be acceptable. Whatever strategy is eventually selected is highly dependent on the following factors.

Uncertainty of Failure

Failures of ORUs on the Space Station have been divided into three basic failure categories. These are failures due to infant mortality, causes that take effect randomly in time, and life limits. The random, and possibly the infant mortality failures, are associated with a large element of uncertainty. Indeed, since the random failures lead to a constant failure rate, occurrences of failures are evenly defused across time, and it is very difficult to predict which ORU will fail in any given time interval. To maintain a spares inventory and to be reasonably certain that a spare will be available when it is needed, an inventory is required that is larger than the actual number of failures that will actually occur. The projections for providing spares for the limited life failures are somewhat easier to determine. This is because the limited life failures tend to occur over a much smaller interval of time. In fact, limited life failures can often be averted by replacing ORUs in advance of their failure. If such a preventive maintenance strategy is used, then spares can be supplied to the station only when they are needed and need not necessarily be stored on board.

Commonality

One of the factors that influences the number of spares needed in the inventory is ORU commonality. If in a given large class of ORUs, all the ORUs can be used interchangeably, then, with a large confidence of having a spare when it is needed, only a small number of the ORUs in that class have to be kept in the spares inventory. On the other hand, if an ORU is unique, has an appreciable chance of failure due to random causes, and must be replaced shortly after failure, then a spare will have to be kept on board the station at all times. In general, the higher the commonality of ORUs, the smaller the required spares inventory will be. It may be that to cope with the large mass transfers to orbit that will be required to maintain a spares inventory of ORUs, more modular ORUs will have to be considered. This implies that parts of the ORU could be changed out rather than the entire ORU. This should also help increase the commonality of replaceable items. It is often possible to use a limited variety of basic parts to construct more complex units.

Level of Acceptable Degraded Performance

In general, it will probably be impractical to replace external ORUs as they fail. Rather, EVAs will only be done once some maximal amount of worksite time has accumulated. This means that consideration must be given to the impact of allowing a failed ORU to remain in a failed state for some period of time. Another reason why a failed ORU may not be replaced immediately is that a spare is not available. As was pointed out above, if a large number of ORUs are unique (and this appears to be the case on the current design of the station), then a spare inventory required to keep the Space Station in a continuous state of repair will have to be at least as large, and possibly somewhat larger, than the number of such ORUs on the station. If the size of such an inventory is impractical, then, again, degraded performance of the Space Station will have to be an acceptable alternative.

The EMTT has concentrated on the maintenance that will be required for the external ORUs. But since a spares inventory will also be needed to maintain the inside of the Space Station, and since there is very likely to be limits on the size of the total inventory, a maintenance strategy for both the inside and outside of the Space Station needs to be considered simultaneously. To the best of our knowledge, this has not been done.

SSF Reconfiguration

In developing recommendations for SSF reconfiguration options which would reduce the total maintenance demand, three tiers of change were initially considered. These were (1) relocation of external ORUs to within an additional pressurized volume within the context of the current SSF architecture and configuration, (2) elimination of as much external infrastructure as possible while using the current systems for providing required functionality, and (3) consideration of alternative sources of functionality.

The EMTT decided to limit this study to the first option. The results of that analysis are contained in Appendix I. However, the EMTT recommends that the SSF Program pursue the other two options. Specifically, the total elimination of the truss and its replacement with pressurized modules in which, and on which, all station elements would be mounted should be evaluated. Of the many parameters which must be managed in a program as large and complex as the Space Station, power and weight demand the closest scrutiny. Considering that many of the recommendations contained within this report if adopted will impact both of these parameters, the EMTT feels it is imperative that the program consider alternative systems for delivering the station elements to orbit and for providing onboard power. Specifically, alternative lift vehicles and a nuclear power source must be accessed.

Recommendations Summary

External Maintenance Task Team Recommendations

The following is a summation of all recommendations from the External Maintenance Task Team. The first 14 recommendations are included in the Executive Summary. The remaining 81 are indexed to the functional areas as worked during the EMTT analysis and the SAIC Blue Ribbon Panel. While some overlap exists among these recommendations, they are all included in order to provide insight into their origins.

Recommendations Summary

1. Develop a plan for accomplishing external maintenance requirements that will occur prior to the completion of Space Station construction.

2. Develop a logistics plan for Space Station which will place the required ORUs on Space Station both prior to its completion and during its 30-year lifetime.

3. Implement all recommendations by this task team for decreasing EVA overhead.

4. Develop a common design for all "box-type" ORUs, and require the implementation of that design uniformly across the Space Station Freedom Program.

5. Require that all external ORUs be replaceable in one hour or less by a single EVA crew member. Exceptions to this would be rare, and made on a case-by-case basis.

6. Design all ORUs for mutual EVA and robotic compatibility with standard interfaces, and require implementation of that standard uniformly across the Space Station Freedom Program.

7. In addition to the robot autonomy currently baselined in the Space Station Freedom Program, implement collision avoidance capability on board to reduce crew overhead for robotic operations.

8. Implement ground control of robots to further reduce crew workload.

9. Consider moving a large number of external ORUs inside, decreasing EVA requirements. Also, consider decreasing the total number of ORUs.

10. Baseline a root-cause analysis and corrective action implementation program for Space Station ORUs. Ensure that sustaining engineering supports reliability growth.

11. Eliminate the current EVA pre-breathe requirement, either by a higher pressure space suit or a lower pressure station.

12. Develop a preventive maintenance and inspection plan for Space Station.

13. Place Space Station maintenance and logistics (including EVA and robotics) under a single command at a NASA center with work package responsibility.

14. Redefine the role of Space Station Freedom to reflect that of a "facility" rather than a "mission." Address the scheduling of regular periods of down-time for maintenance and refurbishment.

ORU Count Recommendations

1. Maintain, augment, and update the ORU characterization data gathered in the ORU database as a permanent program resource.

2. Change the definition of ORU from "the lowest level of component that **can** be replaced" to "the lowest level of component that **should** be replaced" while optimizing all design, operations, and logistics considerations.

Worksite Time Recommendations

1. Formally adopt the EMTT definition of Space Station ORU replacement time across the entire Space Station Program.

Definition
Space Station Freedom ORU Replacement Time

> ORU replacement time begins with the EVA crew member in the required restraints at the worksite, the failed ORU in place, the new ORU temporarily stowed at or near the worksite, and the required EVA tools tethered to the crew member or in the immediate worksite area.
>
> ORU replacement time ends with the EVA crew member in the required restraints at the worksite, the new ORU installed, the failed ORU temporarily stowed at or near the worksite, and the required EVA tools tethered to the crew member or in the immediate worksite area.
>
> ORU replacement time includes EVA tether protocol, EVA checkout of the completed procedures, and any other steps between the beginning and ending configuration.
>
> ORU replacement time is counted as clock time to perform the task, and is independent of the number of EVA crew required. The resulting increase in man hours required it two EVA crew members are needed to perform a task will be accounted for separately.
>
> All activities not included in the above definition will be considered as "EVA Overhead."

2. Develop detailed ORU designs as soon as possible, so that more accurate EVA replacement timelines can be developed.

3. Have all ORU replacement times developed by the EVA Branch of the Mission Operations Directorate at the NASA-Johnson Space Center, using procedures supplied by the individual work packages. These times would then be entered into the database for that ORU, and be the sole source of its replacement time data.

4. Baseline all ORU designs to allow for end-to-end replacement in one hour or less by a single EVA crew member. Exceptions to this should be rare, and allowed only on a case-by-case basis.

5. Standardize ORU design and EVA tools wherever possible. Individual work packages and international partners must be required to conform to a common set of ORUs and EVA tools where design and function permit. (This activity was initiated in March 1990 as part of theEMTT effort, see Appendix G).

6. Incorporate into the design of each ORU a rapid means of functional checkout after replacement is complete.

K-Factor Recommendations

1. Results of the EMTT study should be used to provide design direction for various SSF equipment. If emphasis is applied on the items driving K-Factor values, reduced EVA demand will result. A prime example would be to ruggedize access covers, panel-mounting guides, and connecting fasteners to reduce human-induced damages of the fastening mechanisms and attaching hardware. This should be considered necessary because historically, damage rates for similar types of equipment are shown to be a major factor in causing additional maintenance actions. Accordingly, establish and quantify test requirements for the program.

2. A detailed study of human error correlations should be performed to gain better understanding of drivers which cause humans to err in the space environment. Once drivers are singled out, design efforts should be made to accommodate and reduce the causes. A detailed study is recommended because human-error-induced rates are a significant portion of the overall K-Factor totals.

3. With the appreciable effects of ionizing radiation on electronic equipment, and because SSF has many electronic devices located in the external environment, stringent equipment radiation hardening specifications/processes should be considered.

4. As analyses (such as the FMEAs and CILs) are completed, the ratio (20% critical items to 80% non-critical items) used in developing the environment-induced K-Factor subelement values should be revisited. This is needed because the ratio turns out to be a driving element in the value development. Also, consider requirements for non-critical equipment (e.g., 95% for critical 1 R).

5. Assure that the SSF Program has an effective tracking program and database so that future manned space programs will have quantifiable and traceable maintenance information for use in estimating resource demands. This data will also provide for monitoring SSF Program trends and allow personnel to be alerted to any developing adverse trend conditions. Establish possible "alarm levels" beyond which corrective actions/investigation would be required.

EVA Overhead Recommendations

1. Provide equipment necessary to allow EVA crew members to work independently in separate areas of SSF.

2. Design the CETA ORU carrying provisions to accommodate transport of multiple ORUs, eliminating the need to make more than two trips to the ULC during an EVA (one to retrieve ORUs and one to return them).

3. Design the CETA rail for direct routing to the airlock from either direction on the transverse boom without airlock spur or alpha joint switching mechanism operations.

4. Locate the CETA rail and ULCs in close proximity to one another such that use of the clothesline is not necessary.

5. Provide the capability to store and relocate the PWP components on orbit in any configuration of partial or complete assembly.

6. Design the PWP components for long-term exposure and eliminate the need to stow it in the PWS.

7. Provide the capability to stow a PWP on each CETA and a third on the Mobile Servicing System's MBS.

8. Provide the capability to stow a PWP on the MBS in such a way that it can be deployed onto the SSRMS or installed at a worksite and returned to the MBS by the SSRMS.

9. Provide for storage of one set of tools on each CETA.

10. Provide dedicated PFRs at all sites frequently visited by the EVA crew (i.e., worksite with low MTBFs).

11. Provide dual sets of dedicated PFRs at sites where crew members are likely to be working simultaneously on independent tasks (e.g., ULCs).

12. Provide spare PFRs to enable the crew to leave them in areas with high concentrations of ORUs (e.g., at each pallet), at sites which will be visited again soon, or in any location that is found to warrant a PFR.

13. Investigate potential redesigns or improvements to existing PFR sockets, wrist tethers, and other frequently used EVAS support equipment to improve operational efficiency.

14. Provide an equipment transfer device which enables:
    - Simultaneous transfer of ORUs and support equipment to/from a worksite in a single deployment
    - Efficient operation by a single, unaided EVA crew member
    - Positive control of all objects during transfer operations to prevent inadvertently "bumping" equipment

15. Minimize the number and complexity of ORU restraints required in the ULC, on the CETA, and at the installation site.

16. Investigate telerobotic applications for selected EVA overhead tasks before and after the EVA occurs to directly eliminate those tasks from the EVA timeline.

17. Provide tether points to accommodate attachment of two tethers simultaneously on all equipment which the crew must transfer, hand off, or temporarily stow using tethers.

18. Replace the CSA provided MFR and its stowage on the MBS with stowage provisions for a PWP which can accommodate unassisted deployment, installation, and stowage by the SSRMS.

19. Implement a programmatic requirement to ensure that all EVA tasks must be optimized for performance by one EVA crew member

20. Implement programmatic directions to ensure a proper balance of engineering and operational considerations to design decisions.

Maintenance Demand Recommendations

1. The project should develop a comprehensive maintainability model that should be used to
   - Project maintenance demands as the design of SSF matures
   - Project the logistics and spares inventory that would be required to support proposed design options
   - Establish requirements on the types of measurements that SSF should log as it begins operation

   This model should be part of a more comprehensive supportability model that can be used to gauge design trade-offs in terms of the SSF life cycle cost and performance variables. It is important that these models be developed early in the program to establish the need for the kinds of data that should be collected to be able to predict future maintenance and logistics demands. In the past, NASA has not collected, for example, failure histories in an easily accessible fashion that would allow reliability growth estimates to be made in a routine way. In part, this has greatly complicated the ability to do reliability studies on major programs such as Shuttle.

2. For the current SSF design, projections of maintenance demand imply that SSF will experience a large number of failures as it is being built. This implies that a logistics plan should be one of the first design concepts that should be developed. Provisions for supplying spares, resupply, and maintenance should be in place before any major construction phases are begun. It may be that by starting the SSF design with a logistics concept, a different construction sequence or even a different approach to construction will emerge.

3. The design of SSF should include a graceful degradation policy that will dictate the way cut backs on station performance are made as failures accumulate and are not immediately repaired. This degradation policy should view SSF as a facility that can perform at less than full capacity a substantial part of its life.

4. Since SSF is projected to have some large periodic maintenance demands due to limited life failures, consideration should be given to a dry-dock concept in which periods are set aside to perform a station overhaul with a maintenance crew that is larger than the crew that permanently mans the station.

5. Commonality of parts should be stressed as much as possible in constructing ORUs. For those ORUs for which the dominant failure mode is due to random causes, such as electronic ORUs, consideration should be given to a sub-ORU concept in which parts of the ORU could be repaired at SSF rather than requiring that the entire ORU be brought back for refurbishment on the ground. Establishing commonality at this lower component level should be easier and greatly reduce the amount of weight that needs to be transferred between the ground and orbit. If the ORUs are built in a more modular way, such on-orbit repair could possibly be done inside pressurized modules.

6. Since SSF is being viewed as a stepping stone toward the manned exploration of the planets, it should be a facility in which we learn to do things that will be needed later. In particular, this report points out that maintainability is an important concept in the overall design process. There are, however, many unique problems that have yet to be solved in reliability and maintenance of remote facilities. Much of the research and development in this area has been sponsored by the Department of Defense and the nuclear industry; but, there are problems that are unique to space vehicles. NASA should consider, perhaps jointly with the Department of Defense and the nuclear industry, sponsoring research in this area. The results of this research should be tested on SSF.

Robotics Recommendations

1. Rely on SSF robots to accomplish a majority of the external maintenance workload by Assembly Complete.
2. Define, adopt, and enforce program-wide ORU/robot compatibility design standards.
3. Define, adopt, and enforce program-wide ORU worksite accessibility standards.
4. Implement an on-board collision avoidance capability in the Mobile Service System.
5. Implement a ground-based SSF geometry electronic database ("world model") for uplink initialization of on-board local robot workspace geometries and collision-avoidance algorithms.
6. Implement ground-based remote control of SSF robots for monitoring and control of all robot automatic functions.
7. Implement a rigorous verification program for all robotic functions with special emphasis on all automatic functions.
8. Implement a "robot repair of robots" policy to ensure that maximum utility of robots is achieved with a minimum of EVA expenditure.
9. Integrate the use of all SSF robots (the US Mobile Transporter, the US Flight Telerobotic Servicer, the Canadian Mobile Servicing Center and Special Purpose Dexterous Manipulator, and the Japanese Large Arm and Small Fine Arm) both as maintenance agents and as receivers of maintenance.
10. Begin analyses of SSF robots (as a group) performing multiple serial and multiple concurrent tasks for the purpose of optimizing robot and crew efficiencies.
11. Begin analyses of the use of the teaming of SSF individual robots and sets of robots with EVA astronauts for the performance of maintenance tasks to optimize the efficiencies of the combined set of human and machine maintenance agents.
12. Evaluate the benefits of the use of ground-controlled robots early in the assembly time period in between Shuttle flights to accomplish the maintenance tasks required.
13. Perform all inspections of exterior surfaces through an optimized combination of truss-mounted closed circuit television cameras, the SSF robot cameras, and the use of the SSF robots to position any additional inspection sensors identified in the future.
14. Design all EVA equipment to be robot-compatible ORUs to facilitate robotic assistance prior to, during, and after periods of EVA.

Robot- and EVA-Compatible ORU Recommendations

The results of this initial study have identified the need to develop a standard ORU exchange system that is compatible with EVA and EVR operations. The process of developing these standards should include strong interaction with the work package designers and an extensive testing program. What follows is a list of specific recommendations.

1. Form an External Maintenance Task Force to develop, test and implement ORU design standards.
2. Provide EVA/EVR compatible tools and interfaces as Government Furnished Equipment (GFE) to each work package and international partner.
3. Refine the Box Type ORU Strawman Standards and develop standards for other types of ORU's.
4. Continue to develop and test ORU mock-ups as part of the process of establishing ORU design standards.
5. Determine the cost and benefits of different types of standardization.
6. Develop external maintenance procedures which minimize and optimize the roll of the on-orbit crew through the use of ground control and automated subroutines.
7. Develop a common EVA/EVR ORU exchange tool.
8. Investigate common ORU interfaces across the entire use cycle from ground storage to Space Station application and return.

These recommendations are discussed in more detail below.

Task Force

A strong, high-level NASA Task Force should be formed with a charter to develop standards and specifications, organize external maintenance activities, and bring about the integration of EVA/EVR/IVA and ground control for external maintenance of the SSF. This organization should perform an on-going function of integrating maintenance activities into the design and operation activities of SSF, monitoring, directing, and assisting the work packages' and international partners' activities to ensure compliance with the standards developed by the EMTT.

Standards

The Strawman Standards for Box Type ORU's developed initially at the EMTT Mid-Term Review, should be developed, expanded, and applied to other types of ORU's. The standard should be implemented as specific hardware items (i.e., fasteners, soft dock, mechanisms, tool interface, etc.) that the ORU designers must incorporate directly into their designs.

Trade Study

A trade study should be initiated to highlight the impacts of imposing a standard ORU configuration on the work packages. The focus of the study should address development and life cycle cost, weight, and schedule implications.

Tools

A common EVA/EVR ORU handling and torque tool should be developed. A single torque tool adaptable for EVA and EVR could potentially lower development and manufacturing costs while increasing task performance efficiency through familiarity.

ORU Mock-up Design and Testing

The development of a generic Box Type ORU should be continued and used as a mechanism to develop and test design standards before imposing them on the rest of the SSF Program.

It is recommended that an on-going test and evaluation program be implemented in support of standards development.

Systems Integration

A development program to evaluate the EVA and robotic compatibility of tools and ORUs is needed to provide the proper guidance to the work packages for the detail design and manufacture of their ORUs. This program should be staffed and operated out of JSC using qualified, experienced staff and contractors. Testing and evaluation can be accomplished on site using astronauts and robots in a minimal time period.

It is recommended that mission models be constructed which address different scenarios of EVA/IVA/EVR, ground control, and supervised autonomous operations. The objective is to identify the area that results in the greatest reduction of on-orbit crew resources required for maintenance.

Commonality and compatibility between work packages in the "Box Type" ORU design was found to be lacking. A better understanding of the operational characteristics of robotics and their interfaces is necessary to the success of this program. An on-going program to establish and maintain technical as well as program direction between all work packages and international partners must be established and centrally controlled.

Success of SSF depends on the ability of the astronauts, robots, and ground-based support team to support station operation and maintenance. Integration and standardization of systems and system components, coupled with high reliability, will minimize the external maintenance requirements. Early, rather than later, implementation of the EMTT EVA/EVR ORU standards will provide minimum weight impact to SSF ORUs. The majority of the standards developed by the EMTT can be applied to other types of ORUs.

SSF Reconfiguration Recommendations

In developing recommendations for SSF reconfiguration options which would reduce the total maintenance demand, three tiers of change were initially considered. These were (1) relocation of external ORUs to within an additional pressurized volume within the context of the current station architecture and configuration, (2) elimination of as much external infrastructure as possible while using the current systems for providing required functionality, and (3) consideration of alternative sources of functionality.

The EMTT decided to limit this study to the first option. The results of that analysis are contained in Appendix I. However, the EMTT recommends that the SSF Program pursue the other two options. Specifically, the total elimination of the truss and its replacement with pressurized modules in which, and on which, all station elements would be mounted should be evaluated. Of the many parameters which must be managed in a program as large and complex as the Space Station, power and weight demand the closest scrutiny. Considering many of the recommendations contained within this report will impact both of these parameters, the EMTT feels it is imperative that the program consider alternative systems for delivering the station elements to orbit and for providing on-board power. Specifically, alternative lift vehicles and a nuclear power source must be accessed.

Consider alternative lift vehicle systems and nuclear power source for delivering the station elements to orbit and for providing on-board power.

SAIC Blue Ribbon Panel Recommendations

SAIC Blue Ribbon Panel
Major Recommendations

1. The Panel recommends that the methodology developed and employed by SAIC on this study be extended as applicable to future analytical needs.

2. The Panel recommends that a comparably rigorous methodology and simulation model be maintained throughout the SSF design, assembly, and operational phases.

3. In view of the profound implications of SAIC's analysis, the Panel recommends that SAIC's results be reviewed with appropriate levels of NASA management before proceeding to the next phase in the SSF Program. These results significantly impact the current details of the SSF design, assembly plans, and operational procedures.

4. The Panel recommends that SAIC continue to emphasize that SSF is a facility, not a mission, from both a design and operational philosophy. Examples of such philosophical considerations include the tradeoffs between redundancy and maintainability, the level of fault detection, the operational margins included in facility services, and the impact of technological change.

5. The Panel recommends that SAIC suggest to NASA a review of SSF specifications for consistency with both the concept of a facility and the realistic consideration of the actual construction of that facility.

6. The Panel recommends that SAIC suggest to NASA that the additional steps needed to convert failure rates to EVA maintenance load be subjected to a comparably rigorous analytical review.

SAIC Blue Ribbon Panel General Recommendations

As a primary conclusion of its discussions, the Blue Ribbon Panel recommends that NASA adopt a systematic analysis approach (such as FMECA) as a means for addressing the issues raised by SAIC's analytical results. Based on the Panel's collective experience on other programs, it is believed that such analyses could lead to significant improvements in design, assembly, logistics, and on-going operation. It is also believed that such analyses would lead to short- and long-term options for improvement.

Some, but not all, considerations raised during the Panel's deliberations are given below.

1. The Panel recommends that NASA consider instituting an Inspection & Maintenance protocol for items that degrade over time as a means for reducing failure rate.

2. The Panel recommends that NASA address potential failures due to software-induced damage.

3. It is a recommendation of the Panel that NASA investigate Shuttle plume effects (especially for solar panels).

4. It is a recommendation of the Panel that NASA evaluate EVA efficiency (e.g., suit design and maintenance scheduling).

5. The Panel recommends to NASA that when possible, maintenance should be scheduled to occur concurrently with the arrival of Shuttle crews with particular expertise or crew size.

6. The Panel recommends that NASA thoroughly establish the criticality (consequence) of replacing different ORUs and an algorithm for prioritizing repair.

7. It is the consensus of the Panel that the number of MDMs and other redundant ORUs impacts adversely on the volume of maintenance. The Panel also believes that it may be possible to address this issue without significantly impacting the entire SSF design.

8. The Panel recommends that after SSF failures and failure modes are identified and logged (via a system such as PRACA), a means for closing out failures and prioritizing the closeouts be utilized.

9. The Panel recommends the development and implementation of a "living" systems engineering model to evaluate global tradeoffs (such as logistics to orbit and configuration choices) and "fixes" as needed.

10. The Panel recommends that NASA make a concerted effort to reconstruct the failure history of prior and current programs.

11. The Panel recommends that NASA consider the impacts on SSF equipment and structures (such as airlocks) of factors of "x" increase in the number of maintenance EVAs.

12. The Panel recommends that if NASA intends SSF to have an indefinite life, a preventive maintenance program will need to be in place that addresses scheduling of maintenance actions related to the fundamental infrastructure of SSF.

13. The Panel recommends that NASA recognize that only the base SSF equipment is addressed in the present failure rate and EVA analyses. The ORU failure rates for experimental payloads, etc., which may also have a significant impact on total repair load, are not addressed.

14. It is a recommendation of the Panel that NASA consider the pros and cons of an SSF construction quality assurance program.

15. The Panel recommends that NASA recognize that a Maintenance Significant Item is not equivalent to an ORU and that the ratio between the two needs to be determined to evaluate SSF maintenance requirements.

Appendices

SAIC Failure Rate Analysis

Appendix A

National Aeronautics and Space Administration
Johnson Space Center, Texas

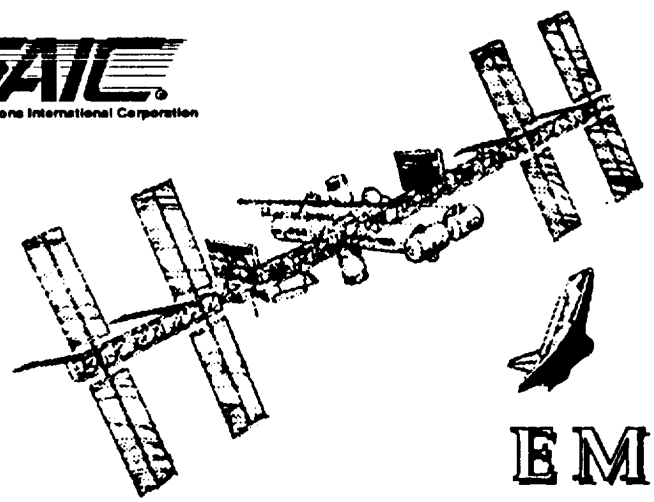
FINAL REPORT

RELIABILITY DATA ANALYSIS for SPACE STATION FREEDOM

EXTERNAL MAINTENANCE TASK TEAM (EMTT)

VOLUME II : TECHNICAL REPORT

SAIC
Science Applications International Corporation



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29 June 1990

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0.0. EXECUTIVE SUMMARY

0.1. Project Background.

As part of the design requirements for Space Station *Freedom* (SSF) NASA allocated a maximum of 130 crew-hours per year for both Station EVA preventative and corrective maintenance. In 1989 the NASA Space Station Program Office performed a study which indicated that more than 1700 crew-hours per year would be required for EVA maintenance alone. This EVA time estimate was developed based on extremely preliminary failure rate and repair time data. Since this EVA time requirement appeared prohibitive JSC established the Space Station *Freedom* External Maintenance Task Team (EMTT) under the direction of William Fisher and Charles Price (hereafter interchangeably called the EMTT and the Fisher-Price team) to refine the estimated EVA maintenance requirements. EMTT recognized that a key element in the estimate was a credible set of reliability data to allow the failure frequency of the EVA relevant components to be obtained. NASA chose the Safety, Reliability, and Risk Assessment (SR &RA) Operation of SAIC to develop this base of reliability data to support the EMTT study.

0.2. Project Objectives.

NASA directed the SAIC SR & RA Team to develop, in less than three months, a set of technically sound, credible, and independently derived reliability (failure rate) data for the over 6000 items of EVA relevant maintenance significance. These EVA Maintenance Significant Items (MSIs) were defined for the purpose of this study to be those items whose failure would require replacement via EVA. This definition was, in some cases, somewhat broader than the NASA-defined term of Orbital Replaceable Unit (ORU), but not substantially so. For this reason the term "ORU" is used throughout this study; however, "ORU" is defined to be identical to the MSI previously defined.

The specific objectives given to SAIC included:

(1) To evaluate the reliability data (failure rates) underlying the various estimates of maintenance-related EVA.

(2) To develop a reliability data base for ORUs requiring EVA for maintenance using the most representative data available. This data could be developed fromORU supplier information, or from surrogate data obtained from analogous equipment in analogous applications.

In addition, NASA asked the SAIC team to provide consulting services to both the Work Package and International Partner organizations and the Fisher-Price team members in the areas of (1) aging of materials and equipment in the Low Earth Orbit (LEO) environment, (2) the evolution of the reliability performance of a long-term program over its expected lifetime, and (3) the technology available for Reliability, Availability, and Maintainability (RAM) analysis and improvement for long-life facilities.

0.3. Project Scope.

The scope of the Reliability Data Analysis (RDA) study was limited to addressing four key issues within the larger scope of the EMTT Study. The EMTT Study in turn was directed at addressing External Maintainance, which includes a significant set of issues within the larger set of issues related to the overall problems of SSF reliability, maintainability, maintenance, safety, spare part allocations, and logistics. It is important to note that this broader set of RAM issues was not excluded from either the EMTT effort or from the RDA effort because they were judged to be any less important than the issues included, but rather because the EMTT and RDA scope were seen as important subsets of the overall ongoing SSF RAM studies.

0.4. Project Ground Rules and Assumptions.

In order to allow for completion of the RDA within schedule constraints, the activity of necessity had to be focused on the key problem areas and based upon a design that was comparable to the design assessed in the original 1989 NASA studies. The study focus was established by setting ground rules and assumptions. These were carefully designed to limit the activity to the core results required while ensuring that all the key issues were covered to the proper depth. The ground rules and assumptions established were:

(1) To develop all data, perform all analysis, and develop all conclusions in a traceable and auditable manner.

(2) To avoid subjective judgements and anecdotal information, and to concentrate on the use of and reporting of only objective data.

(3) To consider the baseline station preliminary design that was in place as of the beginning of the EMTT study (i.e., the snapshot preliminary design available as of 1/1/90).

(4) To only include subsequent changes if they represented refinements of the 1/1/90 design snapshot, that is, if and only if they were implied by the 1/1/90 baseline, and to specifically not include design changes that were in progress even if they would have had significant impact on the resulting failure rate data.

The RDA team recognized early that many of the workpackage designers had already begun to address the failure frequency problems identified either as a part of the 1989 study or through the results of their own internal design reviews. In some instances, by the time the study was underway the designers had developed significantly different design alternatives which they felt offered significant reductions in the expected failure frequency. However it was the primary purpose of the RDA team to review the 1989 study data set from an independent perspective and not to address improvements to that data set which might be expected to design changes. For this reason, while the team recognized that this ground rule might give a distorted picture of the current work package designs which incoproate corrective design features, it was considered essential to use the same design snapshot as was used in the original study as a basis for the current effort.

0.5. Interface With NASA and Contractors.

The study was chartered by the NASA Fisher-Price team to be a truly independent effort. Throughout the study communications between the study team NASA centers, and NASA contractors were limited to obtaining information or data, and design review questions. In no instance did either NASA personnel, in general, or the SSF project team or the Fisher-Price team, attempt to influence either the manner in which the study was conducted or the results. Further, while the design review process is necessarily somewhat adversarial in nature, the NASA and associated contractor personnel completely supported the study team.

0.6. Study Organization.

To ensure that the study results represented the clearest possible objective picture of the in-service failure frequencies to be expected of the 1/1/90 design, a multi-tiered study organization was established. The organization included a core team of SAIC senior professionals, all with experience in this type of project. This core team obtained the actual data utilized and performed the required analysis. All the members of the team had at least five years experience in quantitative reliability, availability, maintainability, and risk analysis for spacecraft, launch vehicles, and ground-based facilities. They were led by a project principal investigator who is an internationally recognized expert in the field of reliability data base development with over 20 years of experience.

This core SAIC team was supplemented by a senior advisory group of reliability, risk and statistical analyst technologists from varied industry and governmental backgrounds. These individuals supported the core team with ongoing advice or particular analytical support as required in their individual skill areas. The members of this group were selected by the principal investigator based solely upon their credentials in the required area of support, and completely independently of where they happened to be employed.

In addition to this advisory group SAIC setup at its own expense an internal independent review. This review panel included senior SAIC personnel who were recognized for their expertise in NASA projects and/or reliability analysis, and who were not members of the SAIC core team. The activities of this panel were directed at reviewing the technical adequacy of the approach, input data, and ongoing analysis to ensure that the project was being conducted consistently with the quality requirements of such a program. In addition during the review process the panel members offered suggestions for improvement in the study activities.

The final and an especially important element of the study organization was the establishment of a team of nationally-recognized experts in reliability data analysis, statistical analysis, EVA requirements, and both manned and unmanned spacecraft design and operations. The objectives of this "Blue Ribbon Panel" (which was headed by former Senator and former astronaut Harrison H. Schmitt) was to obtain an independent review of the project from an external high level perspective. This Blue Ribbon Panel was carefully selected and structured to insure its independence. The panel met in a comprehensive three day session at which the SAIC project director presented the methodological approach and the preliminary results on the first day, and thereafter SAIC's contacts were limited only to answering specific questions and providing a rapporteur. Additionally, no NASA personnel were members of the panel nor were any present during the review session or during the panel deliberations.

As a result of its review, the panel generally concurred with the SAIC approach and indicated that within the time contraints and the limitations placed upon the study that the failure rate data analysis and data obtained were both reasonable and technically sound.

0.7. SAIC Technical Approach.

The entire thrust of the SAIC effort which is shown pictorially in Figure 0-1 can be summarized as an attempt to determine objectively a credible set of reliability data to be used as a basis for estimating the EVA maintenance load expected on SSF throughout its operational lifetime. SAIC used three independent approaches to build this data set for SSF. The first method was to systematically instruct each of the work package analysts on how to develop a traceable, credible data set in each of their respective work package areas, and then to perform a comprehensive audit of the reliability data developed, the approach taken to develop it, and the sources of information utilized. The second method was to use three independent experts to synthesize prototypical SSF ORUs from the technological experience base available and to develop their corresponding reliabilities. (This second method was supplemented during the course of the study by information supplied by NASA/MSFC developed on a similar basis for the Hubble Space Telescope). Finally an independent SAIC activity gathered the historical reliability experience of previously existing programs and developed SSF analogs from this experience set by properly taking into account the differences and similarities between these programs and SSF.

Since the in-service data was limited by history to programs that had not experienced service lives near the 30 year service life of SSF the in-service experience base was limited to only the random failure portion of the SSF data base. This implied that the SSF data base would have to build both the expected initial failure and life limited effects into a random failure base. For this reason the work package analysts were asked to separate the random failure estimates from their life limit estimates, and correspondingly, the data experts were asked to provide only random failure estimates in their synthesis. Since both the structural-mechanical and structural ORUs were judged to have reliabilities which were primarily driven by limited life issues and not by random failure they were not included in the initial comparison. Once a random failure estimate for the relevant SSF ORUs was available from each of these approaches they were compared and the results of the comparison were utilized as the random failure base onto which the initial failure and life limited data could be added.

0.8. Results Summary.

The results of the random failure comparison are shown on a SSF-level basis in Figure 0-2. The figure illustrates the expected distribution of SSF ORU failure rates as developed via both the in-service estimate approach (the top range), and the synthesis approach (the bottom range). In between these two range estimates is placed the point estimate developed independently by the individual work package analysts. It should be noted that not only were these results developed independently, but also that they were provided at significantly different time periods in the study. The first estimates available were those developed according to the synthesis approach; these were available a week before the in- service estimates, which were derived fully two weeks before the work package estimates were developed. As can be seen the in-service and synthesis estimates are consistent with one another, and that the work package point estimate fell in the middle of the range of the other two.

The implications of the results given in Figure 0-2 are clearly shown in Table 0-1. This table indicates how SSF ORUs would be expected to perform from a reliability (failure) perspective according to an average monthly and yearly schedule if random failures alone are considered.

The early failure effects and the life limit effects modify this base in the following way. The early failure effects initially produce a significant increase in the monthly and yearly rate, but this decreases as reliability growth takes hold, and eventually the monthly and yearly rates go below the estimated random rate. The limited life effects cause a peaked increase in the random failure base at and around the associated life limits. This peak is spread out as replacements occur and they significantly diminish for ORUs that experience multiple changeouts due to either random failure or life limit causes throughout the lifetime of SSF. The net result of both of these effects is to raise the overall failure rate above the random failure estimate by a factor slightly above 1.5.

The early failure peak presents particular problems in that failures which occur before the Space Station is completely assembled will be backlogged until replacement logistics and EVA time is available. At present there appears to be no plans to address this backlog, which could be expected to be considerable (from 600-1000 ORUs) if historical experience holds true.

0.9. Implications of Results.

The implications of these results are that the achievement of an average replacement rate of ORUs of 1 per month would require a substantial improvement, over one order of magnitude, above the best in-service performance experienced historically by spacecraft, and that this discrepancy would substantially persist even if all life limited effects were removed.

0.10 Recommendations.

The NASA EMTT has asked SAIC to offer recommendations for Space Station R-A-M improvement. The following suggestions are derived both from the Reliability Data Analysis and from our experience in R-A-M analysis and program development for aerospace, industrial, and power generation applications.

- As noted in the last section, the principal root cause of the projected high maintenance EVA demand is the number of components present. In the short term, therefore, NASA should critically re-evaluate the design itself as well as the design and O&M principles which have led to it. One approach of proven effectiveness is to "zero-base" the design, i.e., to hypothesize a minimum-function configuration without redundancy and without auxiliary monitoring, isolation, and protection components, and then to restore only those components which are essential to safety or mission security.

- The key long-term recommendation of both the SAIC project team and the independent Blue Ribbon Panel is to consider Space Station *Freedom* as a long-term facility rather than a space mission. In other words, NASA should establish design, operating, and maintenance principles which minimize the disadvantages while fully exploiting the advantages of operating a long-term facility. This concept has a number of implications; the major ones are as follows:

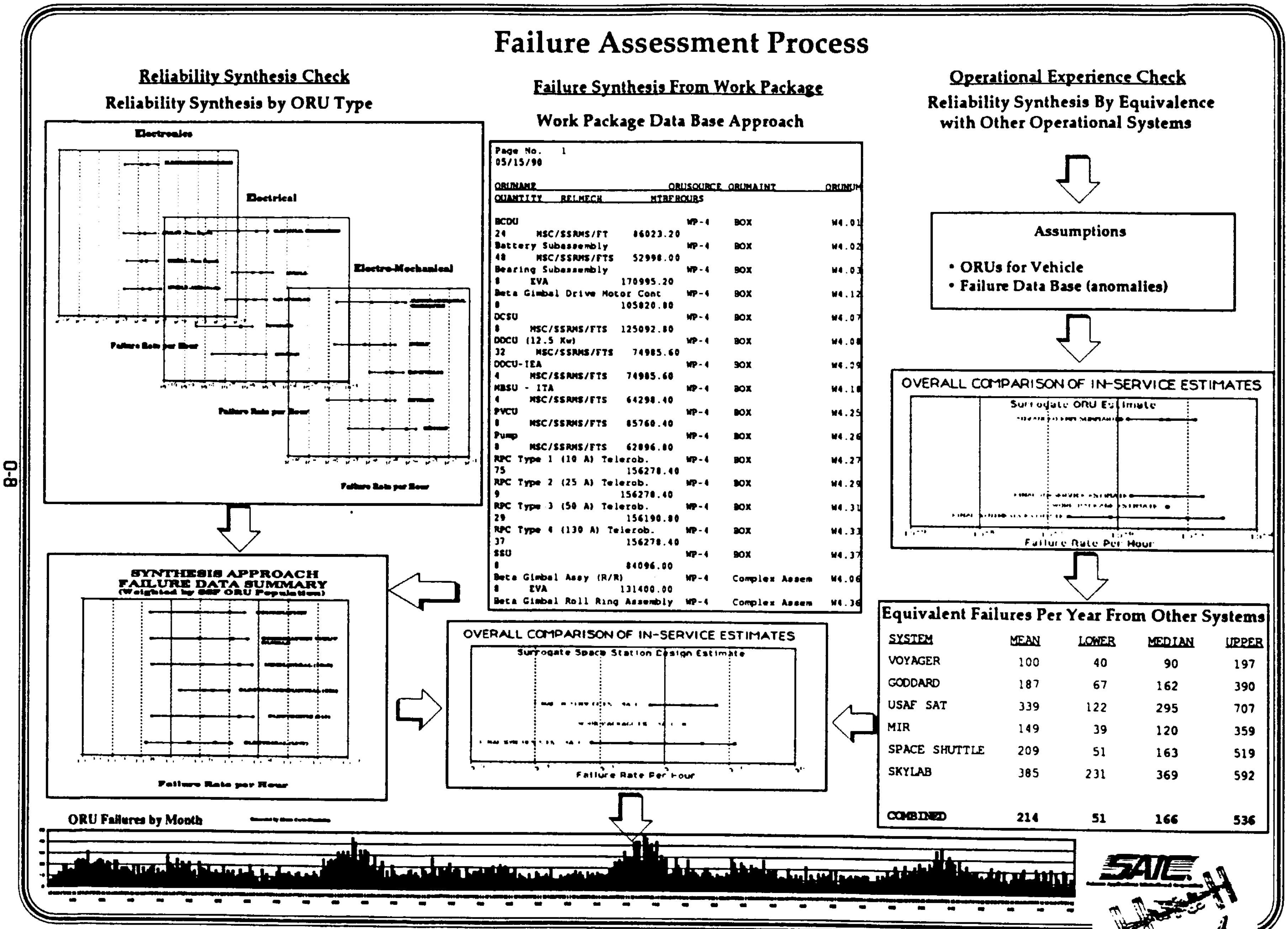
    - Planning and operating a successful long-term facility requires an integrated optimization of such inter-related issues as component reliability, availability, maintainability, risk, life-cycle cost, schedule, spares and supplies logistics, staffing, and training. If this is not already in progress, NASA should promptly initiate the development of an integrated model incorporating these factors, and use it consistently across all Work Packages as a basic top-level planning andevaluation tool.

    - Regardless of the reliability of individual components, and even after feasible decreases in the component population, the Station will still need extensive replacements, refurbishments, andupgrades over its 30-year life. The operators of both industrial facilities and commercial andmilitary aircraft fleets accomodate this situation by periodic maintenance outages or stand-downs, during which normal operations are curtailed and all available resources are concentrated on maintenance and upgrading. NASA should consider the applicability of this principle to the Space Station.

- The 30-year lifetime of *Freedom* will allow long-term monitoring of its performance. NASA should use the resulting information to create a solid R-A-M program combining perform ance tracking and trending, recurring failure identification, root cause analysis and closeout, and a reliability-centered maintenance and logistics program.

- The long lifetime of *Freedom* will also give its human operators time to accumulate profound expertise in its operational characteristics and eccentricities. Based on our experience with other long-term facilities comparable to the Space Station in complexity, experienced human operators can diagnose failures reliably from the information available from relatively simple instrumenation. Therefore, NASA should consider substituting the expertise of experienced facility operators for complex, expensive, and failure-prone monitoring and diagnostic instrumentation.

- This approach requires — and rewards — the creation of a cadre of experienced operators. For example, in the nuclear power industry, otherwis similar plants whoseoperators average more than five years' experience consistently perform better by all significant criteria than plants whose average operator experience is less than five years. NASA should thus minimize the turnover of the operators responsible for its major infrastructure systems, whether they are stationed in orbit or on the ground. (It may be advisable to create a permanent onboard crewposition along the lines of a "chief facilities engineer.")



Failure Assessment Process
Reliability Synthesis Check
Reliability Synthesis by ORU Type
Electronics
Electrical
Electro-Mechanical
Failure Rate per Hour
SYNTHESIS APPROACH
FAILURE DATA SUMMARY
Failure Rate per Hour
ORU Failures by Month
Failure Synthesis From Work Package
Work Package Data Base Approach
Page No. 1
05/15/90
ORUNAME ORUSOURCE ORUMAINT
QUANTITY RELMECH MTBFHOURS
BCDU WP-4 BOX
24 MSC/SSRMS/FT 86023.20
Battery Subassembly WP-4 BOX
48 MSC/SSRMS/FTS 52998.00
Bearing Subassembly WP-4 BOX
8 EVA 170995.20
Beta Gimbal Drive Motor Cont WP-4 BOX
8 105820.80
DCSU WP-4 BOX
8 MSC/SSRMS/FTS 125092.80
DDCU (12.5 Kw) WP-4 BOX
32 MSC/SSRMS/FTS 74985.60
DDCU-IEA WP-4 BOX
4 MSC/SSRMS/FTS 74985.60
MBSU - ITA WP-4 BOX
4 MSC/SSRMS/FTS 64298.40
PVCU WP-4 BOX
8 MSC/SSRMS/FTS 85760.40
Pump WP-4 BOX
8 MSC/SSRMS/FTS 62896.80
RPC Type 1 (10 A) Telerob. WP-4 BOX
75 156278.40
RPC Type 2 (25 A) Telerob. WP-4 BOX
9 156278.40
RPC Type 3 (50 A) Telerob. WP-4 BOX
29 156190.80
RPC Type 4 (130 A) Telerob. WP-4 BOX
37 156278.40
SSU WP-4 BOX
8 84096.00
Beta Gimbal Assy (R/R) WP-4 Complex Assem
8 EVA 131400.00
Beta Gimbal Roll Ring Assembly WP-4 Complex Assem
OVERALL COMPARISON OF IN-SERVICE ESTIMATES
Surrogate Space Station Design Estimate
Failure Rate Per Hour
Operational Experience Check
Reliability Synthesis By Equivalence
with Other Operational Systems
Assumptions
• ORUs for Vehicle
• Failure Data Base (anomalies)
OVERALL COMPARISON OF IN-SERVICE ESTIMATES
Surrogate ORU Estimate
Failure Rate Per Hour
Equivalent Failures Per Year From Other Systems
SYSTEM MEAN LOWER MEDIAN UPPER
VOYAGER 100 40 90 197
GODDARD 187 67 162 390
USAF SAT 339 122 295 707
MIR 149 39 120 359
SPACE SHUTTLE 209 51 163 519
SKYLAB 385 231 369 592
COMBINED 214 51 166 536
SAIC
EMTT

Figure 0.1

SIMULATION OF RANDOM FAILURE EFFECT (CONSTANT FAILURE RATE) USING WORK PACKAGE DATA

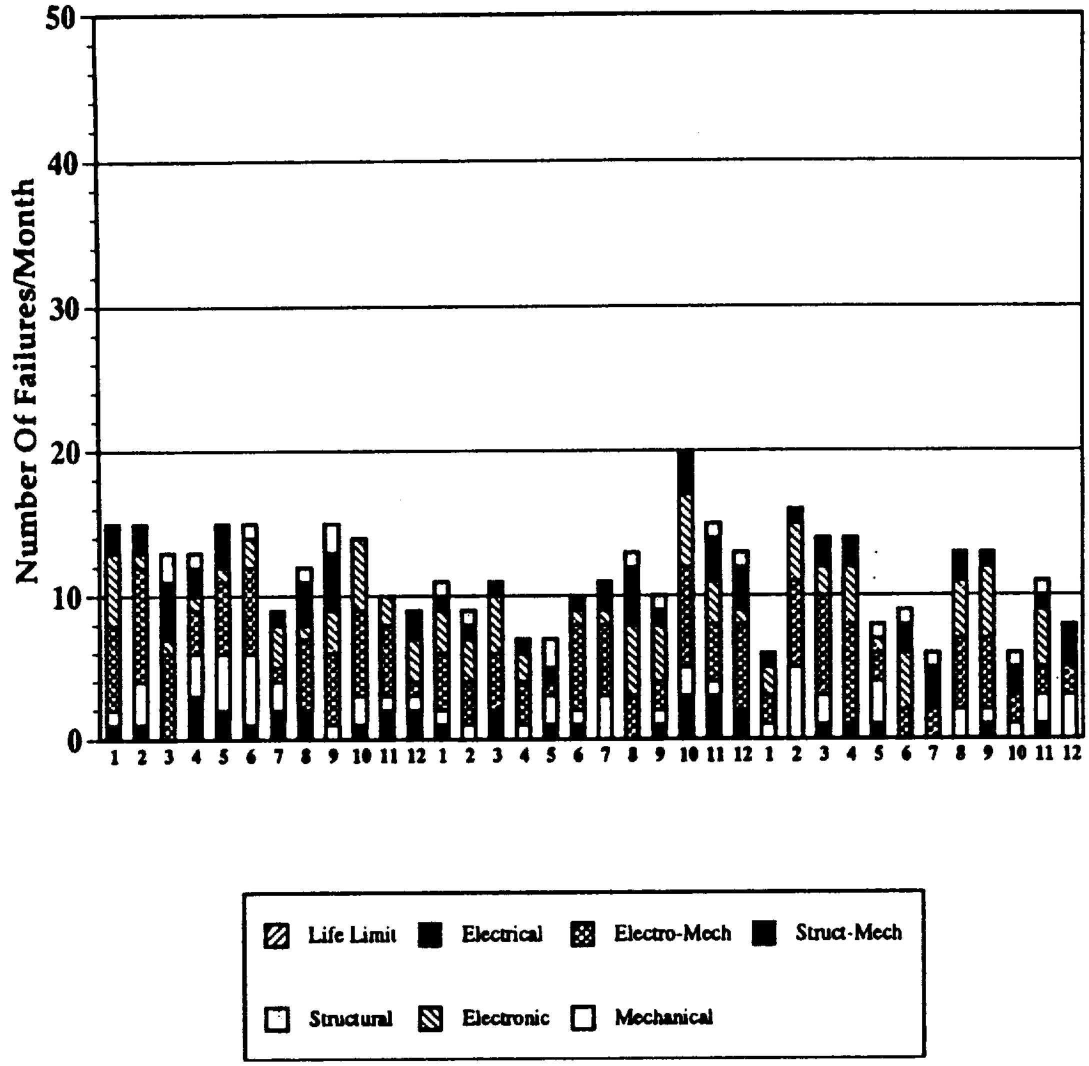


Figure 0.2

SAIC EMTT

Table 0.1

Configuration 1/1/90 - SPACE STATION FREEDOM EXTERNAL ORU FAILURE FREQUENCY COMPARISONS [RANDOM FAILURES ONLY]

		IF SSF WERE BUILT LIKE...	THE EXPECTED NUMBER OF FAILURES WOULD BE... PER MONTH	PER YEAR
HISTORICAL EXPERIENCE	UNMANNED SPACECRAFT	VOYAGER - DEEP SPACE PROBES	8.4	101
		NASA/GODDARD SATELLITE	16.8	202
		AIR FORCE SATELLITE	26.1	313
	MANNED SPACECRAFT	SALYUT/MIR*	12.5	150
		SPACE SHUTTLE	17.4	209
		SKYLAB	32.1	385
	OTHER	NEW FBM SUBMARINES	8.9	101
ESTIMATES		SYNTHESIZED TECHNOLOGY	27.4	329
		WORK PACKAGE DESIGNERS	14.3 (12.1)**	171 (145)**
		HUBBLE SPACE TELESCOPE	11.3	135

*Acknowledged failures

**Based on latest update of SAIC Data Base (6/15/90)

EMTT

1.0. INTRODUCTION.

1.1. Project Background.

In 1989 the NASA Space Station Program Office conducted a preliminary evaluation of the amount of extravehicular activity (EVA) which would be required for corrective maintenance of Space Station *Freedom*. The study was performed with early conceptual design information, generic equipment failure rates, and rough estimates of task times, and predicted that repairs of failed Orbital Replaceable Units (ORUs) located outside the pressurized modules would require approximately 1700 astronaut-hours per year. This maintenance EVA requirement appeared prohibitive for two reasons: first, because EVA is inherently hazardous; and second, because the projection far exceeded the then-current allocations of crew time for maintenance of all kinds — internal as well as external, and preventive as well as corrective.

In response, NASA established the Space Station External Maintenance Task Team (EMTT) headquartered at Johnson Space Center. The EMTT's basic mission was to refine the estimate of the maintenance EVA requirement of Space Station *Freedom*, and if the requirement still appears excessive, to recommend ways to decrease it. To this end, the EMTT requested each of the organizations responsible for a major element of the Space Station (i.e., the four domestic Work Package centers, the International Partners, and/or their contractors) to supply failure rates and other maintenance-related data for each external ORU under its jurisdiction; an EMTT contractor then organized this information into a computerized data base. The initial EMTT analysis of Work Package and International Partner information yielded a preliminary projection of more than 2300 external maintenance EVA astronaut-hours per year, even more than the 1989 study. If valid, this preliminary result would apparently require significant changes in the Space Station program, potentially encompassing such areas as mission, configuration, design rules, schedule, operating and maintenance philosophy, logistics, staffing, and training.

As a result of this preliminary analysis the Space Station *Freedom* Reliability Data Analysis Project was established. The incidence of equipment failures is one of the major determinants of the need for corrective maintenance; therefore a technically and statistically sound failure rate data base is essential to an accurate maintenance prediction. The EMTT recognized that Space Station equipment exists in most cases only as preliminary designs with no operating experience, that the reliability parameters predicted for it are thus subject to question, and that the data developed must be able to withstand the intensive review process that was to be expected in view of the nature of the preliminary results. An independent and highly credible assessment of the external ORU reliability data was needed, and the current project was directed at satisfying this need.

1.2. Project Objectives.

The principal objectives of the Space Station *Freedom* Reliability Data Analysis were the following:

- To assess the technical validity of the methodology used by the Work Packages, International Partners, and their contractors to develop the Space Station external ORU reliability data submitted to the EMTT data base.
- To produce an independent, audited external ORU reliability data base whose data sources and analytical methodology are clearly traceable and auditable.
- To produce an independent prediction of Space Station external maintenance requirements throughout the 30-year design life of the Station.
- To provide consultative support to the EMTT in the fields of R-A-M analysis and improvement, reliability growth, aging of materials and equipment in the low-Earth-orbit environment, and other topics related to Space Station reliability and maintainability.
- To maintain essentially complete independence of any organization involved in planning the Space Station or supplying Space Station equipment.
- To complete the analysis over the 3-month period from 2 April through 1 July, 1990, in order to support NASA's aggressive schedule for completion of the EMTT study.

1.3. SAIC Scope of Effort: a Subset of Key R-A-M Issues.

A full examination of Space Station reliability, availability, and maintainability involves a wide variety of inter-related issues, not all of which SAIC was tasked to consider. Figure 1-1 shows the scope of the SAIC Reliability Data Analysis, and how it relates to the broader charter of the External Maintenance Task Team and to the still-broader spectrum of R-A-M issues which the Space Station program will confront as it goes forward.

SPACE STATION *FREEDOM* RELIABILITY-AVAILABILITY-MAINTAINABILITY ISSUES

1. Random failure rates of Orbital Replaceable Units (ORUs).
2. Life limits of ORUs with deterministic degradation mechanisms.
3. Early failure phenomena.
4. Overall failure prediction over the life of the Station.

SCOPE OF THE SAIC RELIABILITY DATA ANALYSIS PROJECT

5. "K-factors" (ratio of maintenance actions to actual hardware failures).
6. EVA versus robotic repair.
7. Time to repair (including EVA and robotic overhead.)
8. Commonality among ORUs.
9. Corrective maintenance procedures.
10. Preventive maintenance, inspection, surveillance testing, and operational policies.
11. ORU design and materials changes.
12. Station configuration changes.

SCOPE OF THE NASA EXTERNAL MAINTENANCE TASK TEAM

13. Internal maintenance (equipment inside pressurized modules).
14. Spares stocking.
15. Crew staffing and training.
16. Integrated R-A-M-risk-operations-logistics-cost analysis.
17....OTHERS...

KEY R-A-M ISSUES

Figure 1.1

SAIC EMTT

2.0. PROJECT ORGANIZATION AND STRUCTURE.

2.1. Project Organization.

The Safety, Reliability, and Risk Assessment Operation of SAIC was responsible for the Space Station *Freedom* Reliability Data Analysis Project. Figure 2-1 depicts the project organization and the functions of the principal participants. Essentially the project was executed by two teams and monitored by two other teams, although some of individual members of the various teams functioned in several capacities as shown by the organization chart. The composition and functions of the teams which actually performed the analysis are described in the next two sections. The two review teams are discussed in section 2.3, "Quality Assurance."

2.1.1. Core Team.

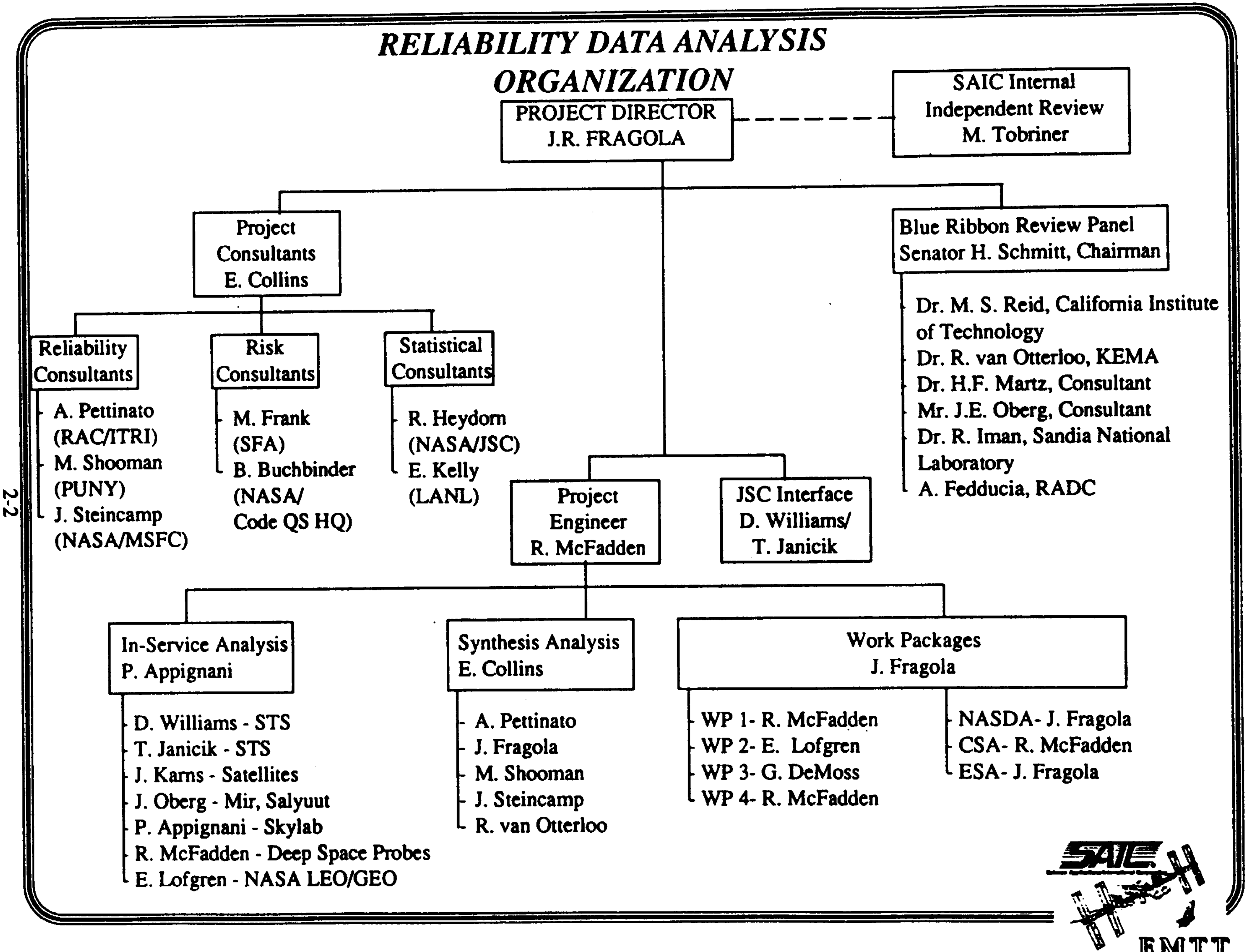
The Core Team was the group of SAIC personnel who are directly responsible for the execution of the project, and included the following:

Peter L. Appignani	Thomas J. Janicik
Erin P. Collins	James J. Karns
Gary M. DeMoss	Ernest V. Lofgren
Joseph R. Fragola	Richard H. McFadden

2.1.2. Senior Advisory Group.

The Senior Advisory Group was a team of recognized senior experts in statistics, reliability analysis, space systems, and space operations, including NASA, SAIC, and outside consultant personnel. This team assisted the Core Team in formulating analytical strategy and methodology, acquiring and organizing data, reviewing the methodology and results, and performing some of the analysis. Senior Advisory Group members included the following:

Benjamin Buchbinder	Anthony Pettinato
Michael Frank	Martin Shooman
Richard Heydorn	James Steincamp
Elizabeth Kelly	Richard van Otterloo
James Oberg	Donald Williams



RELIABILITY DATA ANALYSIS ORGANIZATION
PROJECT DIRECTOR
J.R. FRAGOLA
SAIC Internal
Independent Review
M. Tobriner
Project
Consultants
E. Collins
Blue Ribbon Review Panel
Senator H. Schmitt, Chairman
Dr. M. S. Reid, California Institute of Technology
Dr. R. van Otterloo, KEMA
Dr. H.F. Martz, Consultant
Mr. J.E. Oberg, Consultant
Dr. R. Iman, Sandia National Laboratory
A. Fedducia, RADC
Reliability
Consultants
A. Pettinato (RAC/ITRI)
M. Shooman (PUNY)
J. Steincamp (NASA/MSFC)
Risk
Consultants
M. Frank (SFA)
B. Buchbinder (NASA/ Code QS HQ)
Statistical
Consultants
R. Heydorn (NASA/JSC)
E. Kelly (LANL)
Project
Engineer
R. McFadden
JSC Interface
D. Williams/
T. Janicik
In-Service Analysis
P. Appignani
D. Williams - STS
T. Janicik - STS
J. Karns - Satellites
J. Oberg - Mir, Salyuut
P. Appignani - Skylab
R. McFadden - Deep Space Probes
E. Lofgren - NASA LEO/GEO
Synthesis Analysis
E. Collins
A. Pettinato
J. Fragola
M. Shooman
J. Steincamp
R. van Otterloo
Work Packages
J. Fragola
WP 1- R. McFadden
WP 2- E. Lofgren
WP 3- G. DeMoss
WP 4- R. McFadden
NASDA- J. Fragola
CSA- R. McFadden
ESA- J. Fragola
SAIC
EMTT

Figure 2-1

(Note: Messrs. Oberg and van Otterloo served on both the Senior Advisory Group and the Blue Ribbon Panel. However, in order to ensure the independence of the Blue Ribbon Panel, the only Senior Advisory Group function of these consultants was to provide data on the Soviet space program and on European equipment reliability respectively. They were not part of the discussions of the methodology of the Reliability Data Analysis Project. Also, because Mr. Heydorn was part of the EMTT, his participation in the Data Analysis Project was limited to facilitating access to statistical data and expertise.)

2.2. Contractual Structure and Independence.

For administrative convenience, SAIC performed the Space Station Reliability Data Analysis Project under a subcontract from McDonnell Douglas Space Station Division, Johnson Space Center's prime contractor for Work Package 2 of the Space Station program. However, as noted in section 1.2, a key objective of the project was unquestionable independence of any party involved in planning the Space Station or supplying Space Station equipment. Pursuant to this objective and by explicit contractual provision, SAIC received no direction from either McDonnell-Douglas or any NASA organization other than the EMTT. EMTT's direction was limited to the ground rules discussed in section 2.4 and the format and scheduling of deliverables. The EMTT had no influence on the methodology or results of the project.

2.3. Quality Assurance.

SAIC utilized independent peer review as its primary method of ensuring the technical quality and credibility of the Space Station Reliability Data Analysis. There were two levels of review by two separate teams: an internal quality review by a "red team" of experts employed by SAIC but not involved in the project, and a second review by a Blue Ribbon Panel of distinguished independent experts. The two reviews are described below.

2.3.1. SAIC Corporate Quality Review.

As part of its corporate quality assurance program, SAIC conducts an independent internal quality review of all technology programs which are critical to the national interest. The quality review team for the Space Station Reliability Data Analysis project consisted of the senior SAIC technical and management personnel listed below. All of the internal reviewers have extensive experience in the space flight field, and none had any contact with the project before the review.

Robert Brodowski	Matthew Tobriner
Neil Hutchinson	Jasper Welch
Joseph Levine	Jon Young

The SAIC quality team conducted its review on 4 June 1990. The full-day review session included a presentation of the project methodology and preliminary results, followed by an intensive critical evaluation. The reviewers recommended a number of substantial improvements in both content and format, most of which have been incorporated into the this report.

2.3.2. Blue Ribbon Panel Review.

The Blue Ribbon Panel review was conducted by a team whose members were selected for their internationally-recognized expertise in one or more of the following areas: reliability-availability-maintainability analysis, mathematical statistics, space operations, space flight hardware, and management of space-related activities. (Most members are well qualified in more than one of these areas.) The Panel members were asked to prepare a final, completely independent evaluation of the soundness of the Reliability Data Analysis from two perspectives: as technical experts in its subject matter, and from the standpoint of its value to potential users such as Congress and the top NASA program and headquarters managers.

The members of the Blue Ribbon Panel, their affiliations, and their primary areas of technical expertise are listed below.

Mr. Anthony Feduccia, Director of Reliability Analysis, US Department of Defense Reliability Analysis Center (aerospace equipment reliability analysis)

Dr. Ronald Iman, Senior Member of Technical Staff, Sandia National Laboratory (statistical reliability)

Dr. Harry Martz, Senior Member of Technical Staff, Los Alamos National Laboratory (statistical reliability)

Mr. James E. Oberg, Shuttle flight controller and consultant on the Soviet space program (space operations; space mission planning; US and Soviet space flight history)

Dr. MacGregor S. Reid, Scientific Assistant to the Director, Jet Propulsion Laboratory (design of high-reliability spacecraft; space systems management; space mission planning)

Dr. Harrison Schmitt, Panel chairman, private consultant, former US Senator, former astronaut (space operations, space systems management)

Dr. Richard van Otterloo, Manager of Reliability and Risk Analysis, N.V. Tot Keuring Van Elektrotechnische Materialen (KEMA, the central electrical power research institute of the Netherlands) (reliability- availability-maintainability analysis)

Dr. Jasper Welch, private consultant, former commanding officer of several USAF space operations and research programs (space operations, space systems analysis, space systems management).

With the exception of Messrs. van Otterloo, Welch, and Oberg, none of the Blue Ribbon Panel members had any contact with the Reliability Data Analysis Project prior to the project review during the week of 4 June, 1990. (Mr. Welch participated in both the SAIC internal quality review and the Blue Ribbon Panel. As noted in section 2.1.2, Messrs. Oberg and van Otterloo participated peripherally in the Senior Advisory Group.)

The Blue Ribbon Panel procedure was carefully structured to ensure the Panel's independence of both NASA and SAIC. The SAIC project director presented the methodology and preliminary results of the study on the first day of the review; therefter, SAIC's contacts with the Panel were limited to answering specific questions and providing a reporter to take notes. No NASA personnel were present during the Blue Ribbon Panel review.

The Blue Ribbon panel evaluated the SAIC approach and its results during intensive round-table discussions lasting nearly three days. The Blue Ribbon Panel generally concurred with the SAIC approach. The Panel's formal report contains a variety of recommendations covering improvements in SAIC's methodology and presentation, together with a set of recommendations dealing with Space Station maintainability issues directed to NASA. It is reproduced in Appendix A of this report.

2.4. Project Ground Rules.

The ground rules for the Reliability Data Analysis are summarized below. They resulted from extended discussions between the leaders of the EMTT and the SAIC core team, and are intended to ensure both the technical soundness of the analysis and its credibility.

(1) All data, analyses, results, and conclusions shall be fully traceable to their sources and independently auditable.

(2) Where possible, only objective data and analyses shall be used; the sources, basis, and underlying assumptions of "engineering judgement" and other semi-subjective estimates shall be clearly traceable.

(3) The Space Station configuration as of the beginning of the EMTT study (approximately 1 January 1990) shall be considered the baseline, and ORU reliability data reflecting substantive changes in the configuration after that date shall not be considered. (This rule recognizes that the Space Station design is currently in flux, and that the designs of the several Work Packages and international partners are in different stages of maturity. It was instituted for three reasons: to ensure that the analysis did not degenerate into a continuing attempt to "hit a moving target," to evaluate all Work Packages and International Partners on an equal basis, and, most importantly, to provide a clear basis for comparison with original study results).

(4) Revised ORU data developed after 1 January should be considered only if it satisfies one or more of the following criteria:

(a) it reflects a refinement of the base-line design (e.g. an increase in the number of auxiliary components needed to implement the fundamental design),

(b) it results from a refinement in the methodology for calculating ORU reliability, or

(c) it corrects an analytical or clerical error.

(In particular, data changes reflecting substantive design modifications which appeared to have been motivated by the preliminary EMTT report were excluded.)

2.5. Key Assumptions.

The Space Station *Freedom* Reliability Data Analysis rests upon the three fundamental assumptions about the reliability of space flight equipment which are stated and justified in the following paragraphs.

2.5.1. Three-Term Reliability Function.

The basic external ORU reliability function consists of three terms representing three failure regimes:

(1) an early failure regime,

(2) a constant-failure-rate regime, and

(3) an end-of-life regime.

The basis of this assumption is the well-known "bathtub" reliability-versus- time function. The approaches for handling each regime are discussed in detail later in this document.

2.5.2. Relevance of the Historical Experience of Analogous Equipment.

SAIC has assumed that the historical experience of analogous space-flight and non-space programs is relevant to Space Station reliability, with due allowance for differences in inventory, technology, and environment. This is the basis for the "in-service" approach, in which other spacecraft programs are used as analogs to the Space Station. Reasonably recent other-spacecraft experience is relevant to the Space Station because many spacecraft components are structural, mechanical, electromechanical or electrical in nature; technological change in these areas is relatively slow, so experience is clearly applicable. Even the electronic technologies used in spacecraft have advanced evolutionarily (rather than revolutionarily) at least since the development of integrated solid- state electronics. Both in-service experience and generic reliability data indicate that the per-unit failure rates of typical spacecraft functional units have not changed enough to significantly affect maintenance requirements over the past decade or more.

2.5.3. Relevance of Generic Analogs Developed from Available Technology.

It is assumed that the design principles and reliability-driving characteristics of Space Station external ORUs are typical of equipment with similar functions which is also designed for high reliability. This assumption underlies the "generic ORU synthesis" approach, and is based on the observation that all designers of units intended to perform the same function are working with the same technology base and confront the same design tradeoffs. As a result, if the basic functional requirements and environmental conditions are similar, so are the resulting designs, at least in terms of the major unit-level reliability drivers such as the number of connections and the types and numbers of parts. This commonality allows reliability engineers with hardware design and application experience to formulate "generic" functional units for top-level comparison purposes with considerable confidence.* (The larger and more diverse the equipment set, the better the confidence.*)

*Note: Here the word "confidence" is used in the general dictionary sense and not in the more specific statistical sense.

3.0. SUMMARY OF THE PROJECT APPROACH.

This section describes the general methodology of the Space Station *Freedom* Reliability Data Analysis.

3.1. Information Sources.

The analysis depended on data from these four basic sources:

(1) the computerized data base of ORU reliability data submitted to EMTT by the Work Packages and international partners and maintained by Ocean Systems Engineering (the "EMTT data base");

(2) updated and audited Work Package and international partner data which SAIC collected independently of the EMTT, principally during data acquisition visits to the various NASA centers and contractor facilities;

(3) historical and configuration information on other space flight programs (and one non-space vehicle, a Trident nuclear submarine);

(4) generic component reliability data on components typical of those which will be used in Space Station *Freedom*.

3.2. Multiple Analytical Approach.

To ensure technical soundness and credibility, SAIC used a three-pronged approach in which three independent analytical teams utilized three different methodologies and operated as far as possible on independent sources of basic reliability data, as illustrated in Figure 3.1. The three approaches are outlined below and described in detail in sections 4.0 and 5.0 of this report. Figure 3.2 schematically illustrates the elements of the analysis and how information flowed among them.

(1) Updating, auditing, and analysis of external ORU reliability data furnished by the Work Packages and international partners.

(2) Analysis of "generic ORUs" corresponding functionally to actual *Freedom* external ORUs, synthesized by expert judgement from the current space flight equipment technology base, and supplemented by reliability data on the Hubble Space Telescope ORUs derived from design information. (This is called the "synthesis approach" hereafter for brevity.)

(3) Analysis of the experience of previous space flight programs in order to extract historical failure

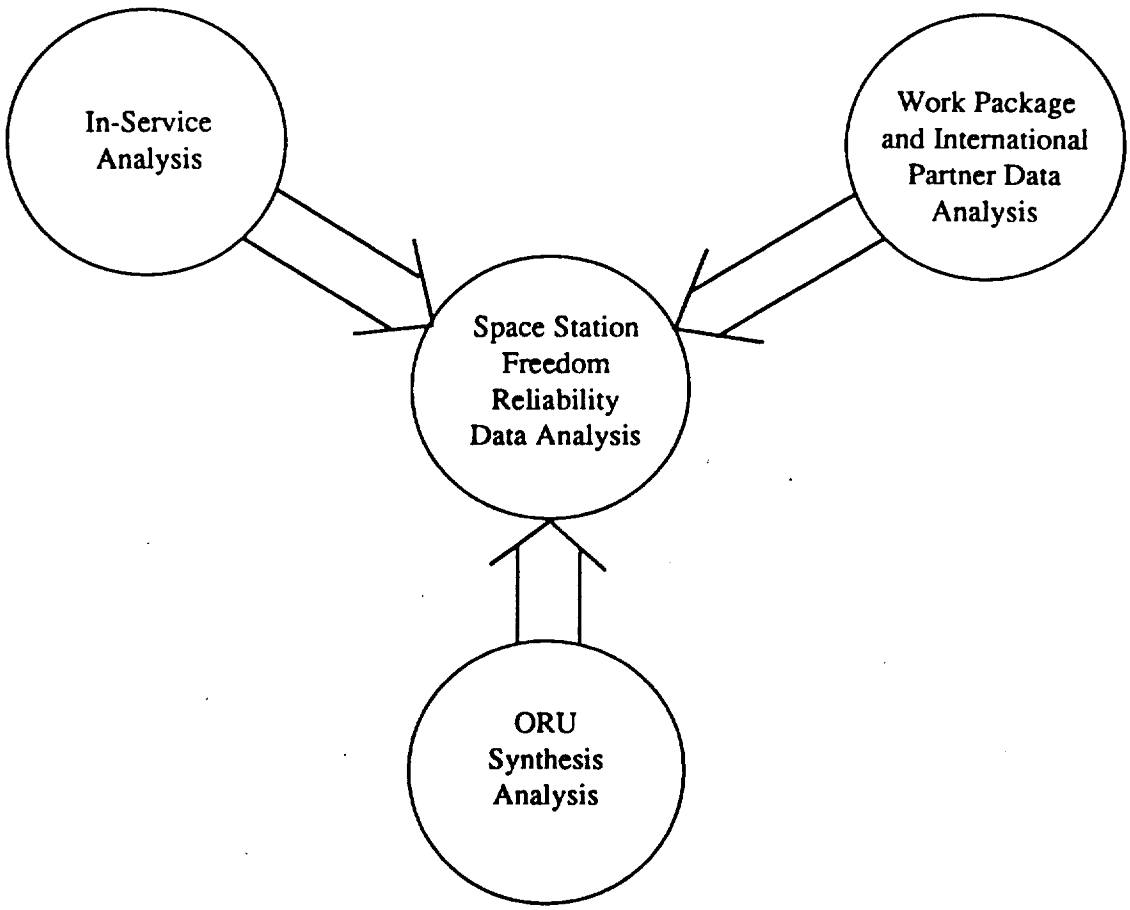


Figure 3.1. Three-Pronged Analytical Approach.

RELIABILITY DATA ANALYSIS PROCESS

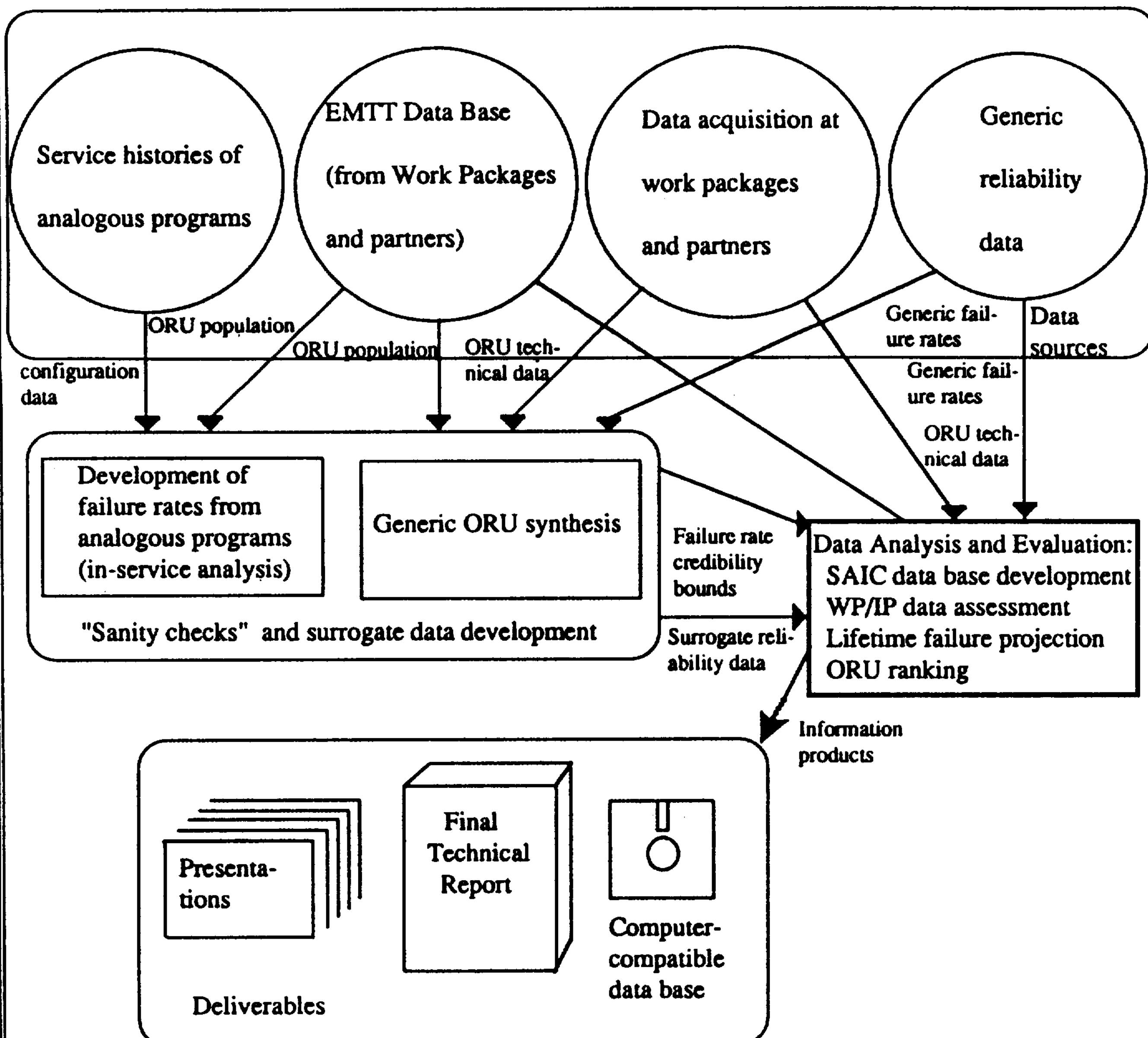


Figure 3.2.

SAIC EMTT

rates for equipment which is functionally and technologically analogous to *Freedom* external ORUs (henceforth called the "in- service" approach).

The latter two approaches were undertaken in order to define the boundaries of credible Space Station ORU failure rates, primarily as a top-level "sanity check" on the Work Package and International Partner ORU reliability data.

3.3. Information Products.

The data from the fundamental sources was processed through the three independent analyses in order to create the information products listed below, which form the basis of this report and other deliverables of the Reliability Data Analysis project.

(1) The audited, traceable, and independent SAIC external ORU reliability data base.

(2) An evaluation of the validity of the ORU reliability estimates prepared by the Work Packages and International Partners.

(3) The boundaries of credible random failure rates for individual Space Station external ORUs and for the entire external ORU set in the base-line Station configuration.

(4) A projection of total external ORU failures by month and year over the expected lifetime of the Space Station.

(5) A ranking of external ORUs according to their projected total failures during the Station lifetime.

4.0. ESTIMATING ORU RANDOM FAILURE RATES.

4.1. ORU Synthesis Analysis.

4.1.1. Generic ORU Synthesis of Expert Opinion.

The synthesis approach to obtaining ORU failure rates is based on a number of assumptions:

(1) Design techniques for various high reliability military and space replaceable modules are similar and SSF will use essentially these same techniques.

(2) The parts and components to be used in SSF will be space-quality ("S-class") parts similar to those used on other projects.

(3) The part and component failure rates (for space and other similar applications) which exist in the literature and in various failure rate manuals, (MIL-HDBK-217E, NPRD-3), are valid for SSF.

(4) Expert equipment failure rate prediction can estimate the distribution of the number of components within typical electrical, mechanical, or electro-mechanical ORU within reasonable accuracy.

(5) Experts in failure rate prediction for analog and digital electronic equipment can estimate the number and type of components for a typical printed circuit board, and the distribution of boards per electronic ORU within reasonable accuracy.

(6) ORUs can be classified as electrical, electronic, mechanical and electro-mechanical.

Estimates produced by three different experts , R. van Otterloo, A. Pettinato, and M. Shooman, as well as a group who designed the Hubble Space Telescope were used in this study.

4.1.1.1. Shooman's Estimates.

Dr. Martin L. Shooman served as an expert in this study. The details of his methods and the data collected in this study appear in this section. As discussed later, the other expert analysts used somewhat similar but independent processes.

An overview of the procedure used to develop electrical ORU failure rate data is shown in Figure 4.1.

The table in Figure 4.1 lists 14 different electrical components which were typical of those to be found on SSF. A full size copy of this data appears in Table 4.1 and will be discussed in further detail shortly.

The histogram in Figure 4.1 shows the distribution of elements per ORU which Dr. Shooman assumed. A full-size copy of the histogram is given in Figure 4.2, where we see that he assumed that 25% of the ORUs would have one electrical element, 40% two elements, 20% three elements, 10% four elements, and the remaining 5% five elements. (Note the same distribution was used for electrical and electro-mechanical elements.) The failure rates were combined with the distribution information by a procedure known as aggregation (mixture sampling). More details on the aggregation process are given in Appendix K. The end result is a range of failure rate data for a typical electrical ORU which is shown as the graph in Figure 4.1.

The data given in Table 4.1 can be described in more detail. In the case of batteries, 13 records of appropriate failure rate data were found in the Nonelectronic Parts Reliability Databook (NPRD-3). Ideally, all these sources would be for space applications; however, there are too few data records for space batteries, and this would have produced too few points to adequately define the failure rate spread. Thus, data was used from any of the following environments: satellite, ground benign, ground fixed, airborne inhabited, and submarine. The minimum, maximum, and median values of failure rate for the 13 sets of data are recorded. The data for the other categories of electrical elements was recorded in a similar manner in Table 4.1.

An identical process was used to generate a database for mechanical and electro-mechanical elements as shown in Tables 4.2 and 4.3.

A similar process was used in the case of electronic ORUs, except that it involved a two-step procedure. The first step was to build a family of six typical analog and digital electronic circuit boards. The second step was to combine the circuit boards to determine a typical analog electronic ORU and a typical digital electronic ORU. The process is illustrated in Figure 4.3.

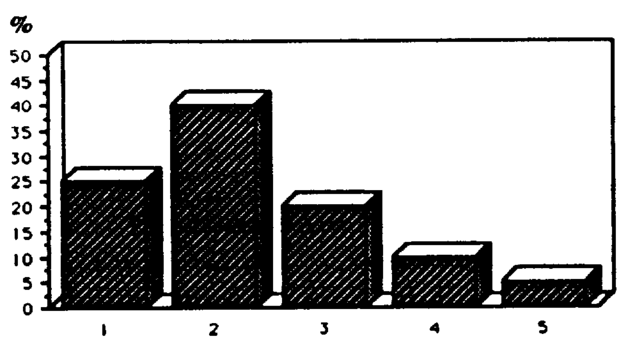
The detailed data for 14 different electronic elements appears in Table 4.4. As an example the integrated circuits were Bipolar and MOS with gate complexities of 1 to 30,000. The data came from MIL-HDBK-217E, and the minimum, median, and maximum failure rates for the 14 sources are given. The configurations of the six different typical electronic boards are given in Table 4.5. The third row in this table defines a digital circuit board of high complexity, DBH, as having 20 resistors, 10 capacitors, no diodes or transistors, 20-D1 integrated circuits, 2-D2 integrated circuits, 1-D4 integrated circuit, 8-M1 memory chips, 8-MZ memory chips, 1-CN board connector, and 1-CB printed circuit board. The result is a set of 6 typical boards and their associated failure rates much is given in Table 4.5. Different distributions are used for analog and digital boards as shown in Figures 4.4 and 4.5.

The analog boards and digital boards are seperately aggregated as shown in Figure 4.3 to obtain the resulting failure rate distributions. Further details on Dr. Shooman's estimates appear in Appendix M.

ELECTRICAL ORU SYNTHESIS FROM ELECTRICAL ELEMENTS - SHOOMAN (SIMILAR TECHNIQUE FOR MECHANICAL AND ELECTRO-MECHANICAL)

Failure Rate Estimates for Typical Electrical Elements

Element Type	Number of records	Sources	<-Failure Rate/Million Hours-> Min	Median	Max
Batteries	13	NPRD-3	0.016	0.75	350
Circuit Breaker	13	NPRD-3	0.075	1.8	11
Connectors	19	NPRD-3	0.013	0.09	3.6
Filter (Elect Power)	7	Mancino 86 217-E [4], RADC 83	0.046	0.18	1.6
Fuse	4	NPRD-3	0.013	0.061	0.44
Fuse Holder	5 [5]	NPRD-3	0.016	0.18	11.5
Heaters	8	NPRD-3	0.27	1.3	7.6
Lamps & Luminaire	5 [1]	NPRD-3	0.1	2.0	8.8
Phovoltaic Cells	[2]	——	—	—	—
Power Capacitor	[2]	——	—	—	—
Power Converter	1 [9]	Mancino 86	—	1.0	—
RF Cable	3 [5]	NPRD-3	0.54	2	13.1
Solid State Switch (SCR, etc.)	5	217-E RADC 83	0.01	0.82	1.38
Wire & Cable	6	IEEEStd.500	0.082	0.52	6.32



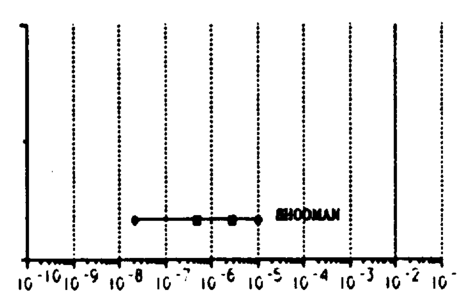
Number of Elements Per ORU

Distribution of number of elements per ORU for Electro-Mechanical, Mechanical, and Electrical Elements.

AGGREGATION OF ELECTRICAL ELEMENTS

RESULT

ELECTRICAL FAILURE RATE DATA



Failure Rate per hour

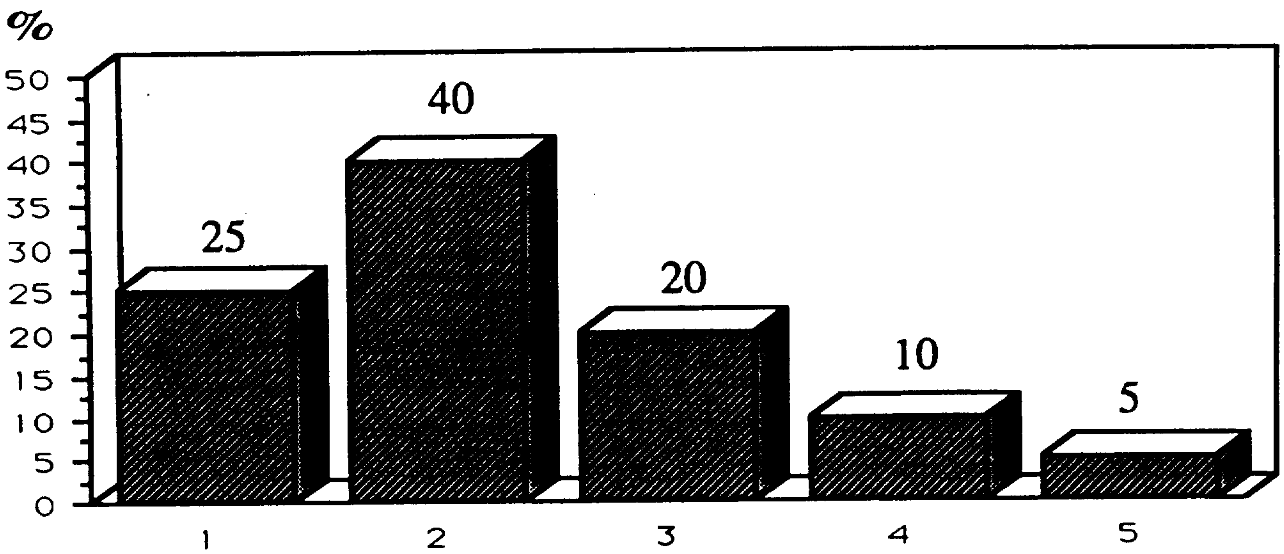
Figure 4.1.

EMTT

Table 4.1. Failure Rate Estimates for Typical Electrical Elements.
(Min., Median, Max.)

Element Type	Number of records	Sources	Min	Median	Max
			<-Failure Rate/Million Hours->		
Batteries	13	NPRD-3	0.016	0.75	350
Circuit Breaker	13	NPRD-3	0.075	1.8	11
Connectors	19	NPRD-3	0.013	0.09	3.6
Filter (Elect Power)	7	Mancino 86[3], 217-E [4], RADC 83 [8]	0.046	0.18	1.6
Fuse	4	NPRD-3	0.013	0.061	0.44
Fuse Holder	5 [5]	NPRD-3	0.016	0.18	11.5
Heaters	8	NPRD-3	0.27	1.3	7.6
Lamps & Luminaire	5 [1]	NPRD-3	0.1	2.0	8.8
Phovoltaic Cells	[2]	-------	---		
Power Capacitor	[2]	-------	---		
Power Converter	1 [9]	Mancino 86[3]	---	1.0	---
RF Cable	3 [5]	NPRD-3	0.54	2	13.1
Solid State Switch (SCR, etc.)	5	217 -E [6], RADC 83 [7]	0.01	0.82	1.38
Wire & Cable	6	IEEE Std. 500 [10]	0.032	0.52	6.32
			Ave	0.89	

[1] Use data for a similar device, emergency lights used instead of luminaire.
[2] No data for this element type
[3] V.R. Mancino, V.R. Monshaw, W. J. Slusark [RCA-Astro-Electronics], "Reliability Considerations for Communications Satellites", Proceedings Annual Reliability and Maintainability Symposium, 1986, pp. 389-396.
[4] MILHDBK-217E, Oct. 1986, Sec. 5.1.18-4.
[5] Other environments included.
[6] MILHDBK-217E, Oct. 1986, Sec. 5.1.3.6-3, 40 deg. C, 50% power stress, (Quality factor = 0.5, environment factor = 1, forward current factor = 1).
[7] D. W. Coit and J.J. Steinkirchner, [IIT Research Institute] "Reliability Modeling of Critical Electronic Devices", RADC-TR-83-108, May 1983, p.166.
[8] D. W. Coit and J.J. Steinkirchner, [IIT Research Institute] "Reliability Modeling of Critical Electronic Devices", RADC-TR-83-108, May 1983, pp.153,4.
[9] Use data for a similar device, power conditioner used instead of power converter.
[10] "IEEE Guide to the Collection and Presentation of Electrical, Electronic, and Sensing Component Reliability Data for Nuclear-Power Generating Stations, IEEE Std. 500-1977, IEEE, NY 1977, pp. 522-525, (Copper conductor, per 1000 circuit feet, for cables, joints, terminations, and penetrations.)



Number of Elements Per ORU

Distribution of Number of Elements per ORU for Electro-Mechanical, Mechanical, and Electrical Elements.

Figure 4.2.

SAIC EMTT

Table 4.2. Failure Rate Estimates for Typical Mechanical Elements.

Element Type	Number of records	Sources	<-Failure Rate/Million Hours-> Min	Median	Max
Bearing Assembly	16	NPRD-3	0.01	2.1	14
Brake	5	NPRD-3	0.87	5.2	750
Bushing	3	NPRD-3	0.048	1.03	14.5
Clutch	3	NPRD-3[4,5]	0.58	1.7	2.4
Coupling	2	NPRD-3	1.4	2.7	5.2
Filters	6	NPRD-3	0.034	1.22	3
Fittings	4	NPRD-3	0.42	2	19
Gear, Assembly,Shaft	5	NPRD-3[4]	0.17	0.58	2.4
Gimbal	1	NPRD-3[4,6]	---	7.8	---
Heat Exchanger	5	NPRD-3	0.92	4.2	27.5
Hoses	1	NPRD-3	1.18	1.74	2.56
Manifolds	3	NPRD-3	0.62	1.1	27
Pump	11	NPRD-3	0.02	7.2	330
Radiators	[2]	----	---	---	---
Regulator, Pressure	6	NPRD-3	0.95	14	730
Rotary Joint	2	NPRD-3	0.4	12.5	395
Seals	9	NPRD-3	0.025	1.55	62
Valve (Pneumatic)	14	NPRD-3	0.019	14	71
Weld Joint	1	NPRD-3	0.03	0.045	0.065
			Ave	4.48	

[1] Use data for a similar device, a synchro.
[2] No data for this element type
[3] Since only one data record is available, the 20% and 80% confidence interval values were used for min and max.
[4] Listed under heading "Mechanical Device".
[5] Other environments included.

Table 4.3. Failure Rate Estimates for Typical Electromechanical Elements.

Element Type	Number of records	Sources	Min	Median	Max
			<-Failure Rate/Million Hours->		
Accumulator	1 [3]	NPRD-3	0.07	0.345	1.08
Actuator (Not Hydraulic or Pneu.)	7	NPRD-3	0.062	0.47	400
Antenna	4	NPRD-3	1.65	92	610
Compressor & Motor (Air)	2	NPRD-3	3.74	14	52
Drive Module	[2]				
Electric Motor	39	NPRD-3	0.22	5.5	250
Instruments & Indicators	12	NPRD-3	2.4	20.5	460
Position Encoder (Synchro [1])	13	NPRD-3	0.135	2.5	330
Relays	48	NPRD-3	0.013	1.0	22
Sensors	5	NPRD-3	0.055	7	88
Slip Rings	4	NPRD-3	0.11	0.6	40
Solenoid and Solenoid Valve	6	NPRD-3	0.29	2.2	65
Transducers	14	NPRD-3	0.58	55	275
			Ave	16.7	

[1] Use data for a similar device, a synchro.
[2] No data for this element type
[3] Since only one data record is available, the 20% and 80% confidence interval values were used for min and max.

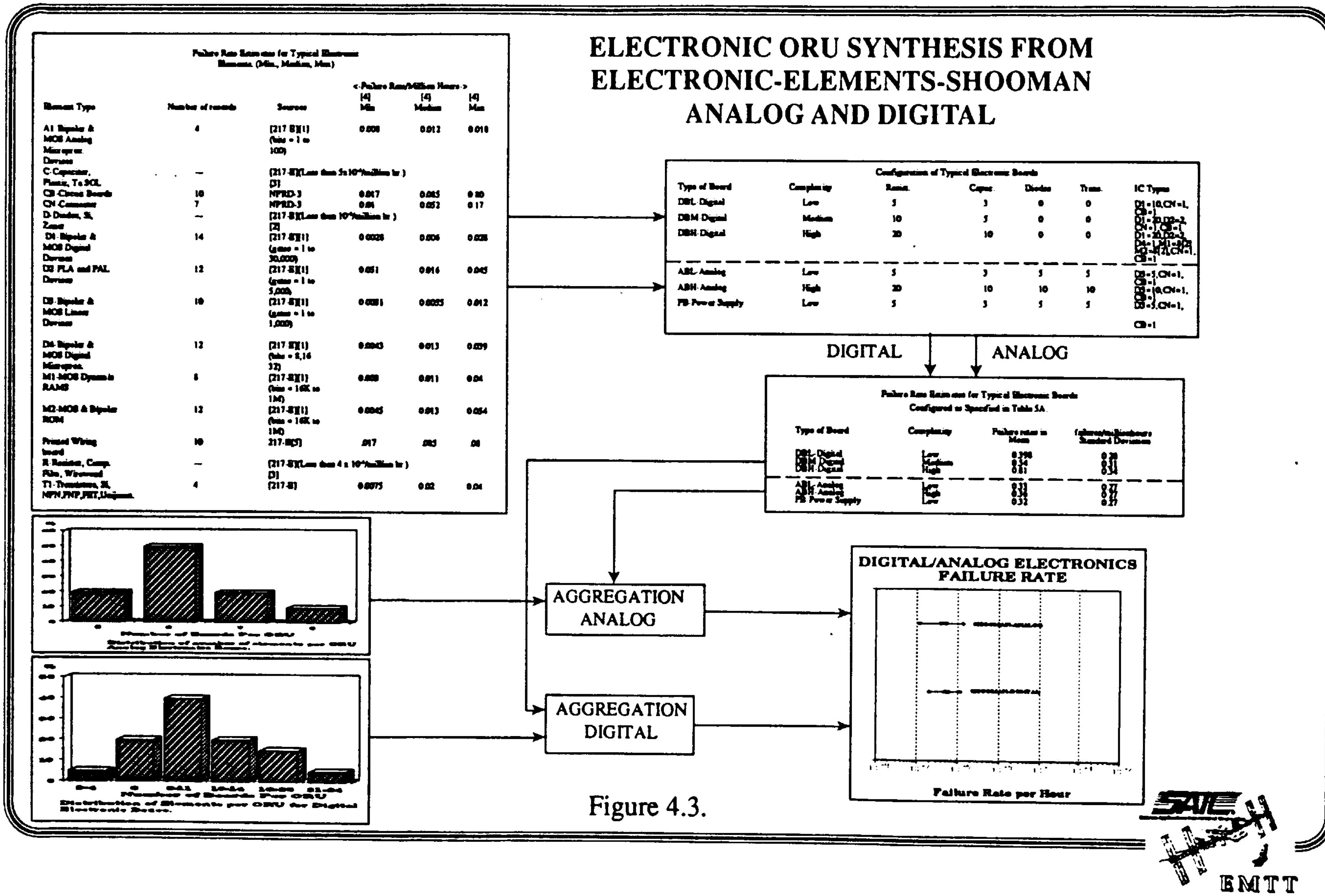

ELECTRONIC ORU SYNTHESIS FROM
ELECTRONIC-ELEMENTS-SHOOMAN
ANALOG AND DIGITAL
DIGITAL
ANALOG
AGGREGATION ANALOG
AGGREGATION DIGITAL
DIGITAL/ANALOG ELECTRONICS FAILURE RATE
Failure Rate per Hour
EMTT

Figure 4.3.

Table 4.4. Failure Rate Estimates for Typical Electronic Elements.
(Min., Median, Max.)

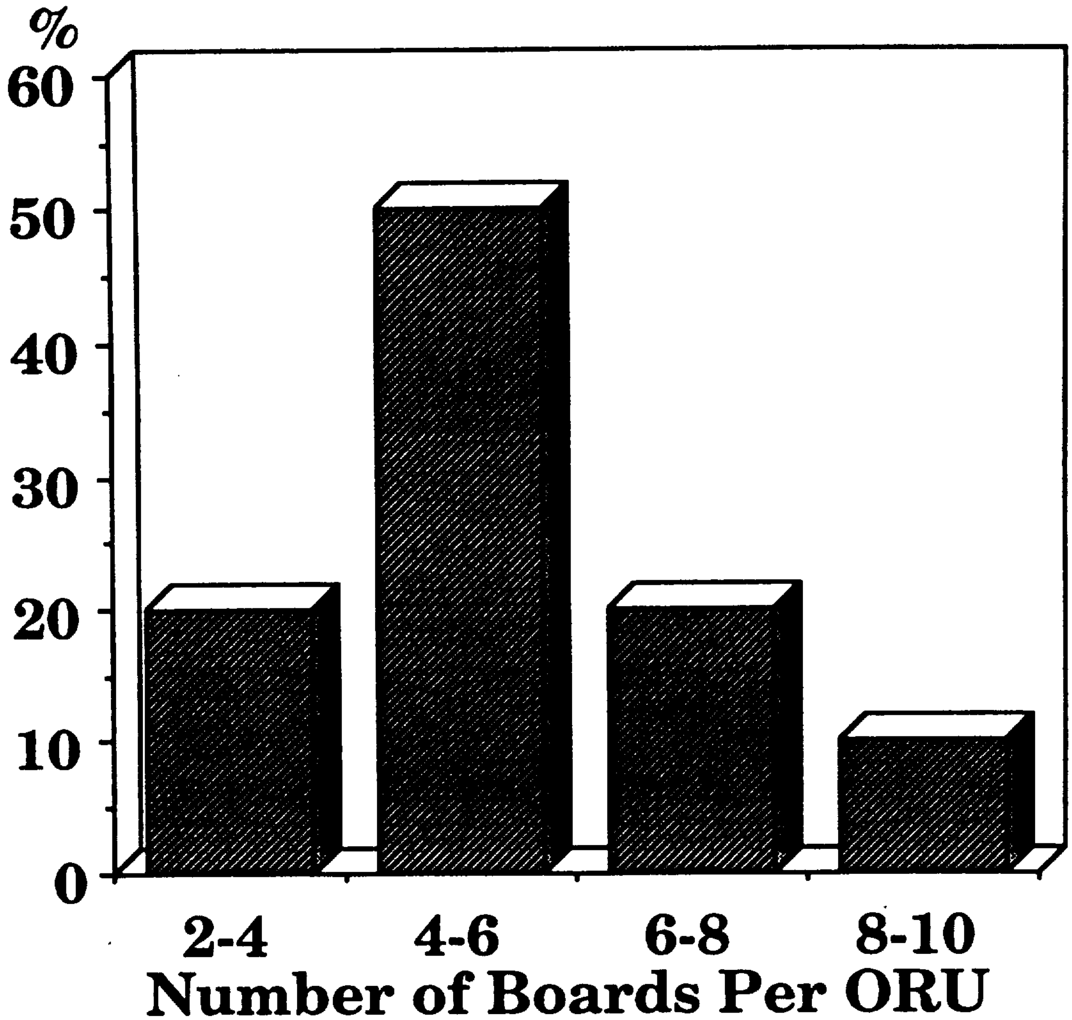
Element Type	Number of records	Sources	<-Failure Rate/Million Hours-> [4] Min	[4] Median	[4] Max
A1-Bipolar & MOS Analog Microproc. Devices	4	[217-E][1] (bits = 1 to 100)	0.008	0.012	0.018
C-Capacitor, Plastic, Ta SOL	---	[217-E](Less than 5 x10-4/million hr.) [3]			
CB-Circuit Boards	10	NPRD-3	0.017	0.085	0.80
CN-Connector Printed wiring board	7	NPRD-3 217-E[5]	0.01	0.052	0.17
D-Diodes, Si, Zener	---	[217-E] (Less than 10-5/million hr.) [2]			
D1-Bipolar & MOS Digital Devices	14	[217-E][1] (gates = 1 to 30,000)	0.0028	0.006	0.028
D2-PLA and PAL Devices	12	[217-E][1] (gates = 1 to 5,000)	0.051	0.016	0.045
D3-Bipolar & MOS Linear	10	[217-E][1] (gates = 1 to Devices 1,000)	0.0031	0.0055	0.012
D4-Bipolar & MOS Digital Microproc.	12	[217-E][1] (bits = 8,16,32)	0.0043	0.013	0.039
M1-MOS Dynamic RAMS	8	[217-E][1] (bits = 16K to 1M)	0.003	.011	0.04
M2-MOS & Bipolar ROM	12	[217-E][1] (bits = 16K to 1M)	0.0045	0.013	0.054
Printed Wiring board	10	217-E[5]	0.017	0.085	0.08
R-Resistor, Comp. Film, Wirewound	---	[217-E](Less than 4 x10-4/million hr.) [3]			
T1-Transistors, Si, NPN,PNP,FET,Unijunct.	4	[217-E] [2]	0.0075	0.02	0.04

[1] MIL-HDBK-217E, Oct. 1986. Quality factor = 0.25 for milstd. S level parts.
[2] MIL-HDBK-217E, Oct. 1986. Quality factor = 0.1 for JANTXV std. level.
[3] MIL-HDBK-217E, Oct. 1986. Quality factor = 0.03 for milstd. S level parts.
[4] Generic failure rates have been multiplied by the appropriate quality factors.
[5] MIL-HDBK-217E, Oct. 1986, p. 5.2-41

Table 4.5. Failure Rate Estimates for Typical Electronic Boards.

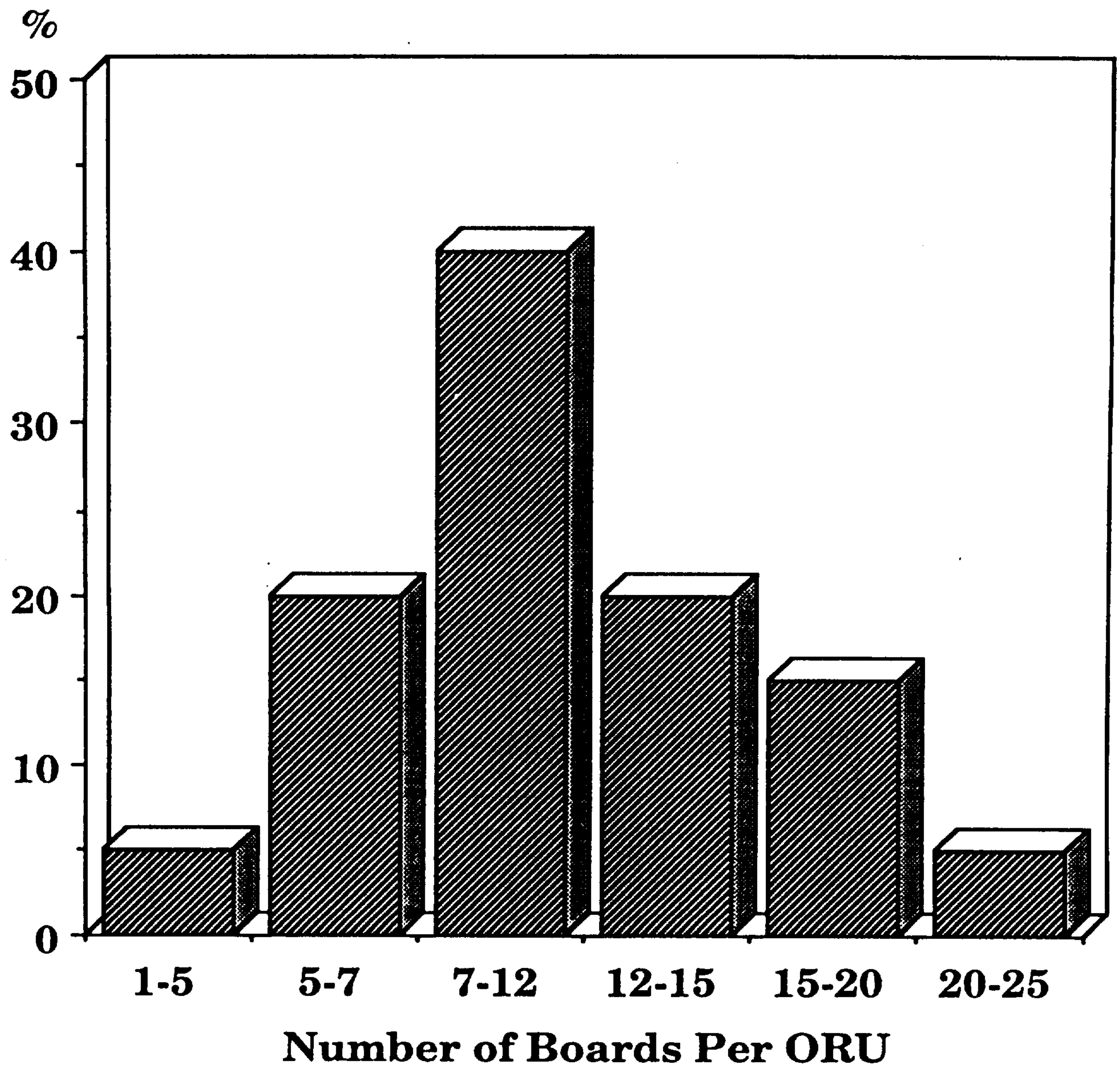
Type of Board	Complexity	Failure rates in failures/million hours[1] Mean	Standard Deviation
DBL-Digital	Low	0.398	0.28
DBM-Digital	Medium	0.54	0.31
DBH-Digital	High	0.81	0.34
ABL-Analog	Low	0.33	0.27
ABH-Analog	High	0.36	0.27
PB-Power Supply	Low	0.32	0.27

[1] Note that the failure rates of the printed circuit board and to a lesser extent the connector play a significant role in the board failure rates given below. These failure rate values should be cross checked with independent data.



Distribution of Number of Elements per ORU for Analog Electronic Boxes

Figure 4.4.



Distribution of Elements per ORU for Digital Electronic Boxes

Figure 4.5.

4.1.1.2. Pettinato Estimates.

Mr. Anthony Pettinato produced estimates for the failure rate range of typical electrical, mechanical, electro-mechanical, electronic-analog and electronic-digital ORUs. The techniques he used were similar to those of Dr. Shooman. Mr. Pettinato is cognizant of the failure rate data sources available to the Reliability Analysis Center at Rome Air Development Center, and he used his professional expertise to choose the best mixture of data sources. His distributions for components per board were similar but slightly different than the ones which Dr. Shooman used. For the number of elements per ORU, the weightings developed by Dr. Shooman (Fig. 4.2, 4.4 and 4.5) were used. (See Appendix M for further details).

4.1.1.3. van Otterloo Estimates.

Dr. Richard van Otterloo produced a set of estimates for the range of failure rates of electrical, mechanical, electro-mechanical, electronic-analog and electronic-digital ORUs. He based his estimates on the best available information on European space programs and his experience in the risk and reliability analysis field. A list of the sources whech he used is given in Table 4.6. The estimates he arrived at appear in Table 4.7.

Table 4.6. Data Sources Used by van Otterloo in Developing Estimates.

1. Specific studies done at KEMA concerning the collection of failure rates of components, systems, or subsystems such as:

- the collection of reliability and availability data of personal computers
- the collection of failure data of computerized.control systems
- failure data analysis of traffic control systems.

2. Years of experience with the System Reliability Data Bank (SRS-UKAEA) and the CEDB (Component Event Data Bank) of EURATOM in Ispra, Italy.

3. Contacts with ESTEC in Noordwijk were to no avail. It was suggested that there was no information available.

4. Failure data given in the failure data banks mentioned below:

- *Electronic Reliability Data, A Guide to Selected Components,* Institution of Electrical Engineers, London and New York. The Gresham Press, Old Woking, Surrey.
- A.E. Green, A.J. Bourne, *Reliability Technology,* Wiley-Interscience, ISBN 0 471 32480 9.
- *IEEE Guide to the Collection and Presentation of Electrical, Electronic, and Sensing Component Reliability Data for Nuclear Power Generating Stations.* IEEE Std. 500-1977, IEEE Standards Board, The Institute of Electrical and Electronics Engineers, Inc. , 345 East 47th Street, New York, NY 10017.
- *Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,* WASH-1400 (NUREG 75/014), Appendix III - Failure Data, National Technical Information Service, Springfield Virginia 22161 USA.
- *Deutsche Risikostudie Kernkraftwerke.* Fachband 3: Zuverlassigkeitsdaten und Betriebserfahrungen. GRS-A-463 (juli 1980), Glockengasse 2, 5000 Koln 1.
- *OREDA, Offshore Reliability Data,* printed by A/S Veritas - Huset, ISBN 82 515 0087 7.

Table 4.7. Failure Rate Data Estimates Developed by van Otterloo.

ORU Type	5% Point	Median	95% Point
	← Failures/million hours →		
Electronics			
Analog	1.0	3.0	10
Digital	0.5	2.0	10
Electrical	0.1	1.0	10
Electro-mechanical	1.0	7.0	50
Mechanical	1.0	10.0	100

4.1.2. Synthesis from Hubble Space Telescope (HST).

The recently launched Hubble Space Telescope (HST) is the only NASA spacecraft that has been designed for manned servicing. (Other spacecraft have been designed for un-manned servicing, and one of these, Solar Max, was serviced via EVA, but it was not designed that way.) For this reason the HST equipment is packaged into modules which are replaceable on-orbit in a fashion similar to SSF. The replaceable modules on HST are the closest genuine hardware analog to the SSF ORUs. Therefore when HST has operated through a number of manned refurbishment cycles it should provide truly valuable operational data which will be very relevant to SSF. Unfortunately, HST has only recently been launched, and so only scant operational information is available. However, since HST is planned for on-orbit maintenance, NASA/MSFC has developed a logistics model to help plan for the eventual replacement of ORUs. As with SSF the MSFC reliability engineers were required to make estimates of the failure rates of the HST ORUs to be able to simulate the operation and refurbishment of HST. The resulting failure rate estimates are contained within the simulation model documented in the internal MSFC report, HST OPSIM (F. Pizzano) MSFC/CTII. Unfortunately, because the failure rates were not considered an end in themselves, detailed traceable documentation of their development was unavailable to the SAIC team. However, discussions with MSFC personnel convinced the SAIC principal investigator that the HST data was developed in a manner consistent with the Work Package and synthesis data and therefore should be considered as an independent basis for comparison with these other sources.

Since the HST equipment was already in ORUs the number of ORUs on HST did not need to be estimated (as was the case for the in-service analysis examples), but was given directly by the line count of ORUs on HST. MSFC classified the ORUs by type using a similar, but slightly different classification scheme than that used in this study. For this reason some of the ORUs had to be reclassified. The changes occurred mainly in which ORUs were considered to be electro-mechanical and the reclassification had the effect of increasing this category at the expense of the electronic and mechanical categories.

In addition MSFC did not segregate the failure rates from the life limits and therefore some items were given negligible random failure rates to indicate that their failure was dominated by life limiting effects. (The assignment of a zero failure rate to heaters is an example). Since the comparison was to be made on a random failure basis only these were removed from the population for consistency. This reclassification and removal effort resulted in the breakdown of ORU classes given in Table 4.8.

Table 4.8.

Electronic [EA]	41
Electrical [EO]	17
Electro-mechanical [EM]	25
Mechanical [M]	1
Total	84

This population of ORUs and their associated failure rates were aggregated using the SAIC proprietary computer code CARP™ to produce distributions of ORU failure rates representative of the established SSF ORU classes. The resulting distributions for each ORU type class were used to compare to the expert derived synthesis generated distributions for each applicable class. The comparison of the resulting distribution with the synthesis distributions is shown in Figures 4.6 through 4.10.

4.1.3. Combining ORU Failure Rates -Experts and Hubble.

The preceeding sections have described how the expert opinions and Hubble data were used to synthesize ranges of failure rate data for the various components. In this section we describe how the various data estimates are combined to yield the distribution of failure rates for a typical electrical, mechanical, electro-mechanical, electronic-analog, or electronic-digital ORU. Then as a second step, each of the ORU types is combined and weighted to yield the failure distribution of a typical generic ORU.

In Figure 4.11 we see a graphical representation of the various steps in the synthesis procedure.

The top left of the Figure shows the estimates from Hubble, van Otterloo, Pettinato, and Shooman for electric ORUs. The four data sets are aggregated as shown in Figure 4.11 to obtain a generic failure rate for electrical ORUs. The result is shown in the center of the figure where the range, median, and mean of the failure rate data is shown. Similar estimates are derived for the other data and the results are weighted and aggregated to obtain the failure rate of a generic ORU. The weighting factors of 1312, 1046, 868, and 327 represent the approximate number of ORUs in each category.

The synthesis procedure for mechanical and electro-mechanical components is identical to that shown for electrical components in Figure 4.11. A slightly different procedure is used in the case of electronic ORUs.

The synthesis procedure for electronic ORUs is shown in Figure 4.12.

As shown in the figure, the three experts gave separate estimates for analog and digital electronics and these are aggregated separately as a first step. The composite estimates are aggregated a second time along with the electronic values for Hubble to produce a generic electronic ORU distribution. The electronic ORUs are weighted and aggregated to obtain an overall generic distribution as shown.

Synthesis Approach Space Station ORU Data Estimates - All Electronics

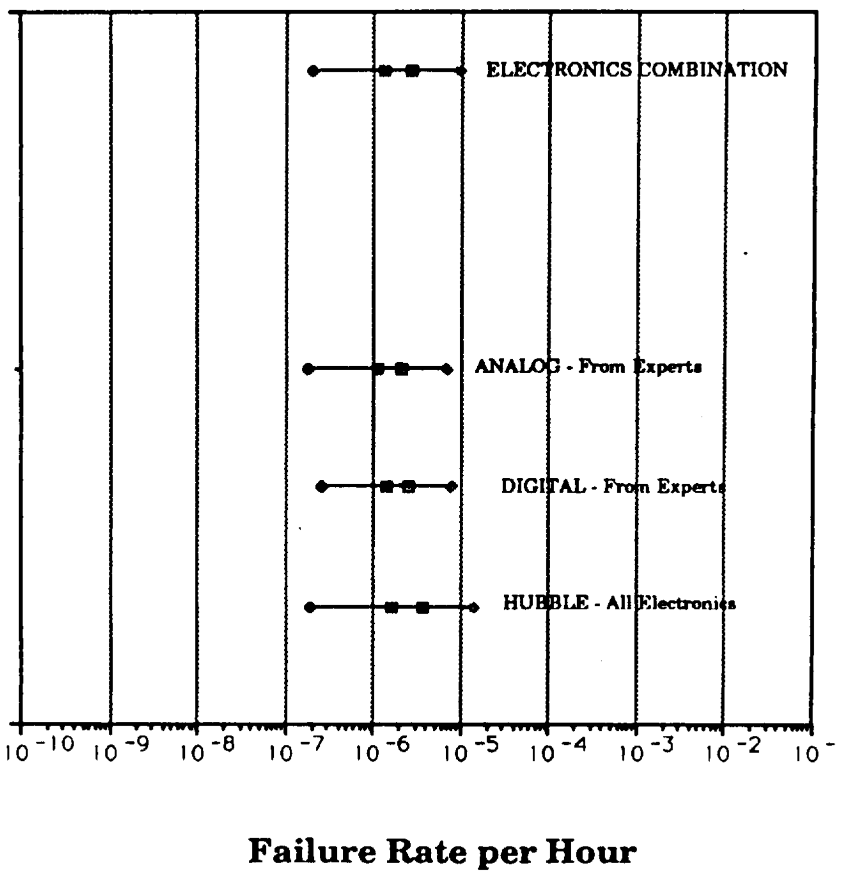


Figure 4.6.

Synthesis Approach Space Station ORU Data Estimates - Electrical

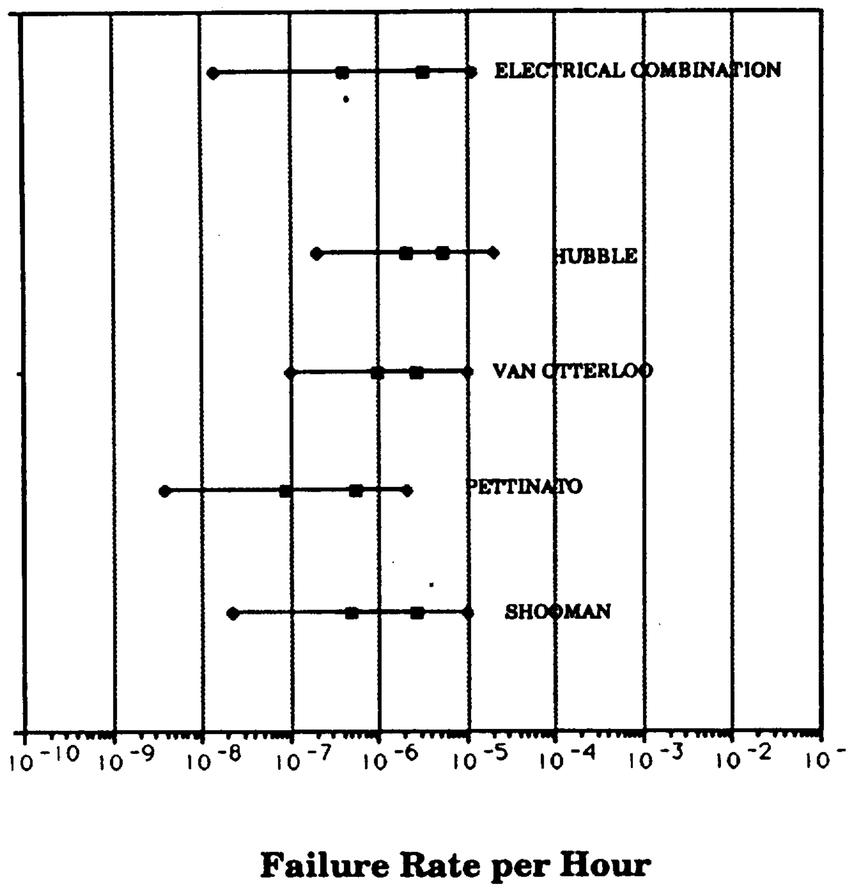


Figure 4.7.

Synthesis Approach Space Station ORU Data Estimates - Electro-Mechanical

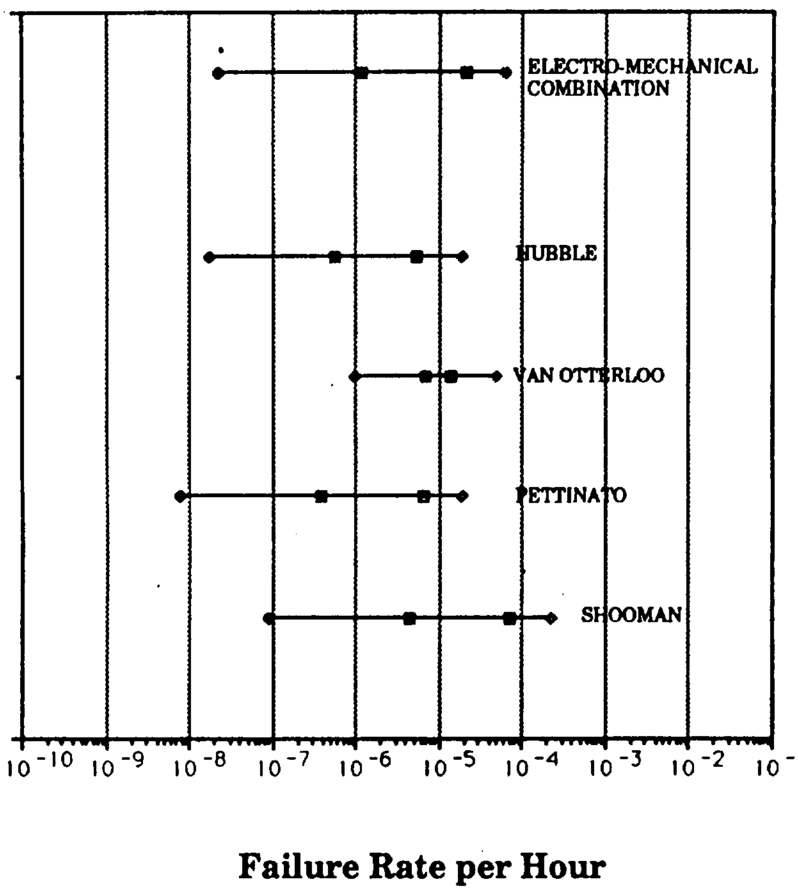


Figure 4.8.

EMTT

Synthesis Approach Space Station ORU Data Estimates - Mechanical

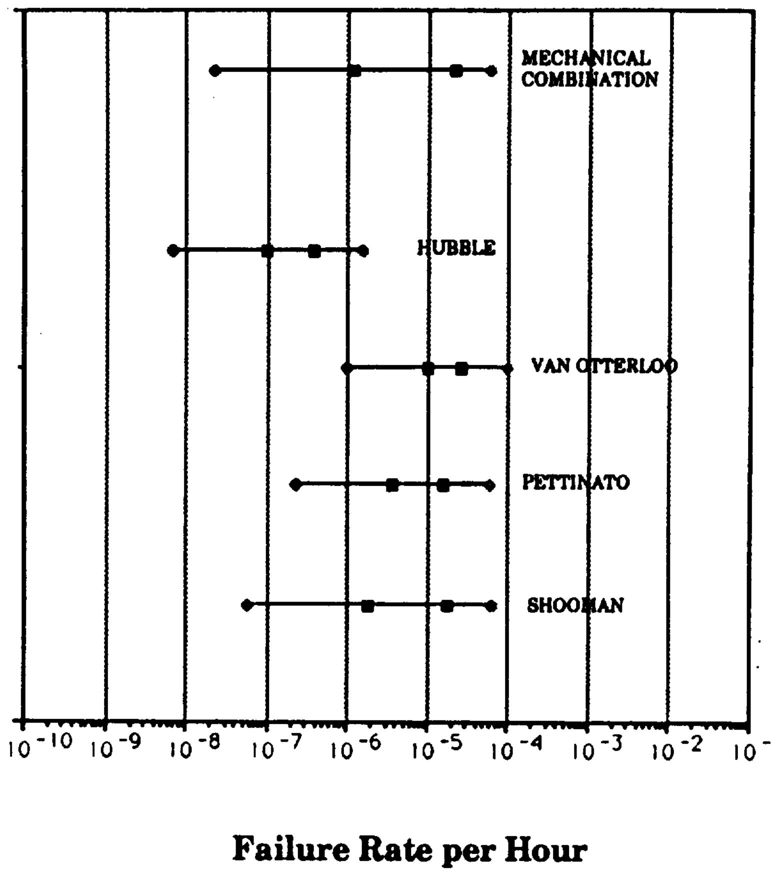
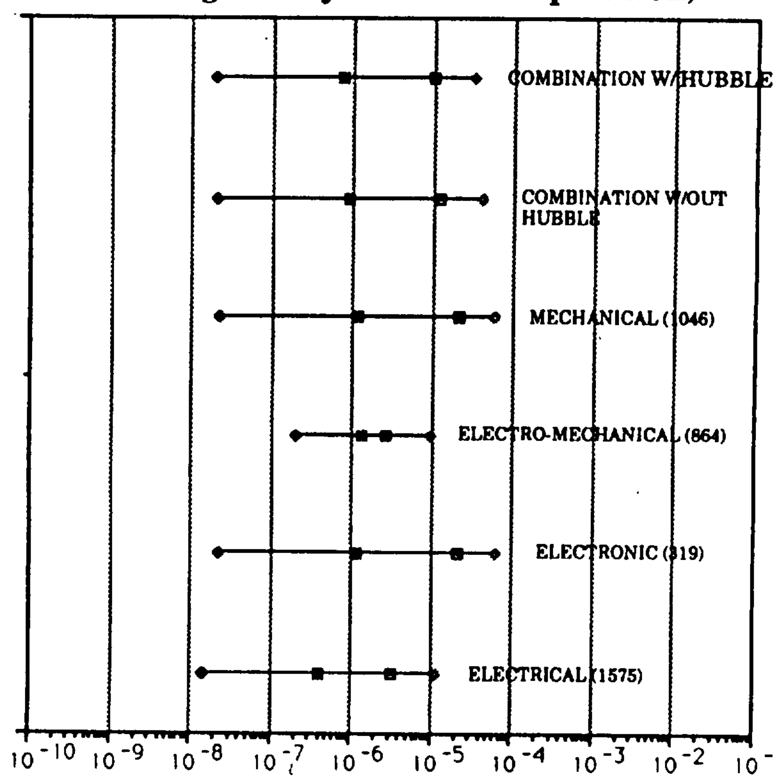


Figure 4.9.

SYNTHESIS APPROACH
FAILURE DATA SUMMARY
(Weighted by SSF ORU Population)



Failure Rate per Hour

Figure 4.10.

EMTT

SYNTHESIS OF EXPERT OPINION
(ELECTRICAL, MECHANICAL, ELECTRO-MECHANICAL)

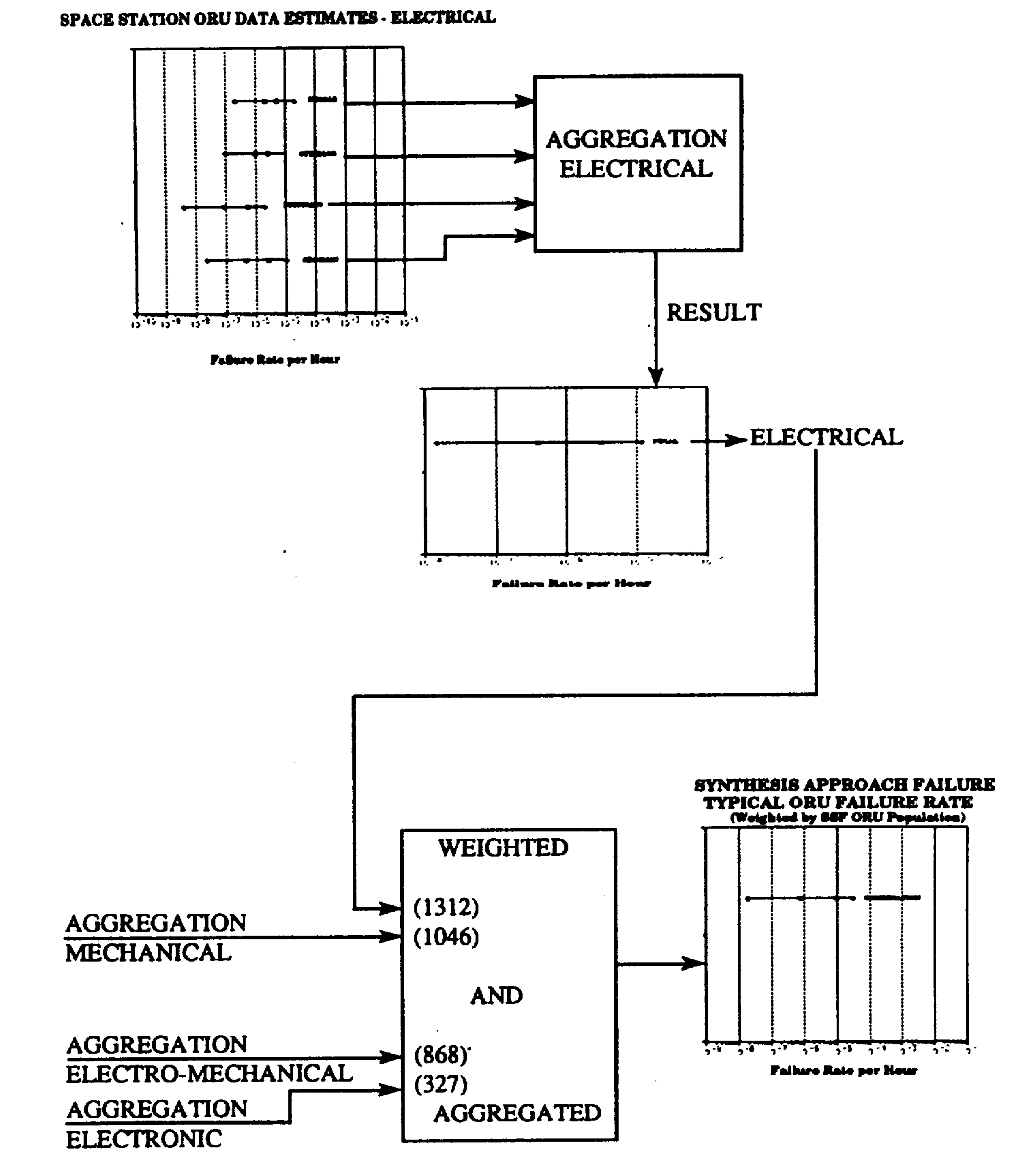


Figure 4.11.

SYNTHESIS OF EXPERT OPINION (ELECTRONIC-ANALOG & DIGITAL)

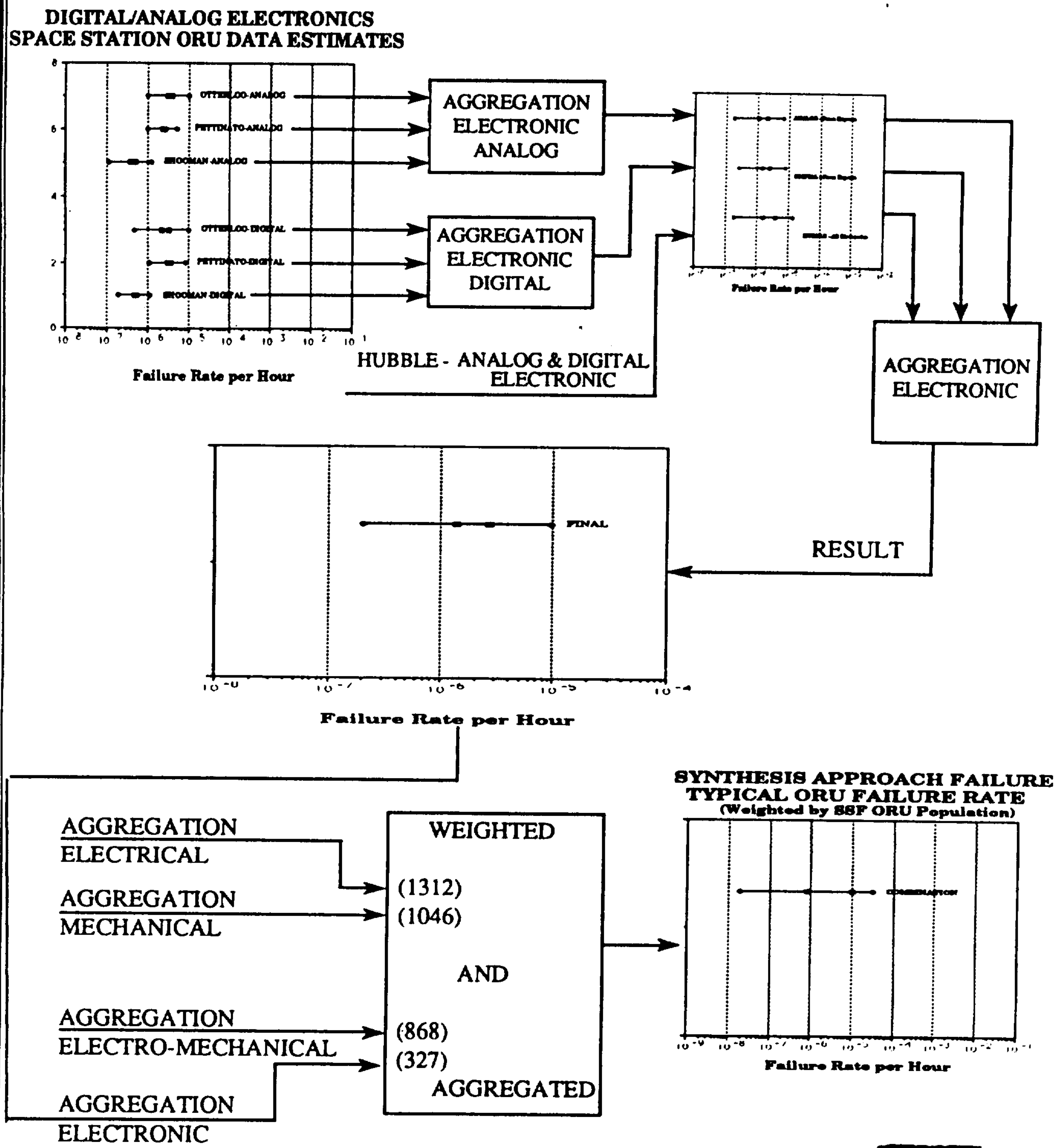


Figure 4.12.

4.2. In-Service Analysis.

The objective of the in-service analysis was to find analogs for Space Station *Freedom* (SSF) among existing, in-service systems and to use historical failure data from those systems to predict the incidence of random failures on *Freedom*. SAIC selected a wide variety of civilian and military programs for this analysis, and received help from a number of sources. In particular, SAIC gratefully acknowledges the assistance of the following organizations for their help in providing failure data:

Johnson Space Center
Jet Propulsion Laboratory
Goddard Space Flight Center
Kennedy Space Center
Marshall Space Flight Center
US Air Force Space Systems Division
US Air Force Rome Air Development Center, Reliability Analysis Center
US Naval Sea Systems Command

4.2.1. Analogs Studied.

The 73 Space Station analogs selected and studied were:

(1) *Voyager* I and II

(2) 19 NASA Goddard Satellites

LANDSAT-2	TDRS-1
LANDSAT-3	TDRS-3
LANDSAT-4	AMPTE
LANDSAT-5	DE-1
NIMBUS-5	DE-2
NIMBUS-6	ERBS
NIMBUS-7	ISEE-1
OSS-1	ISEE-3
SMM	IUE
SAGE	

(3) 45 USAF Satellites

DMSP	(13 Spacecraft)
NAVSTAR-GPS	(10 Spacecraft)
FLTSAT	(6 Spacecraft)
DSCS II	(13 Spacecraft)
DSCS III	(3 Spacecraft)

(4) *Mir*

(5) Space Shuttle
(4 Orbiters)
(6) *Skylab*

(7) Nuclear Submarines
USS *Ohio* (Trident)

4.2.2. Assessment Process.

The assessment process SAIC used in this analysis was as follows: 1. Analyze the analog failure data to determine the number of failures or events which, if they had occurred on a Space Station external component, would require EVA to correct or investigate. 2. Determine the exposure, or cumulative operating time, of the analog being evaluated. 3. Calculate the gross failure rate for the analog as the ratio of the number of failures to the exposure. 4. Estimate the number of non-structural "equivalent ORUs" the analog would have if it had been designed for on-orbit servicing. The ratio of the actual number of non- structural SSF external ORUs to the number of "equivalent ORUs" on the analog is the scale-up factor which adjusts the failure experience on the analog to Space Station. 5. Calculate the SSF equivalent failure rate by multiplying the gross failure rate of the analog by the scale-up factor.

The distribution of "equivalent SSF ORUs" for each of the analogs were selected using an informal Delphi technique. The analysts involved were familiar with both the analog design and general SSF ORU design from Work Package reviews. Equivalent ORU distributions were selected before the analog failure data was analyzed. The distributions were then "anchored" to prevent the possibility that analysts might subconsciously adjust ratios to fit their preconceptions. For the Goddard and USAF satellites, the distribution of equivalent ORUs was selected for the 64 satellites as a class. This process led to some minor anomalies, notably in comparing Goddard satellites to USAF satellites, but creates a more statistically sound study. The reference number of SSF ORUs, 3553, is the count of non-structural ORUs extracted from the EMTT data base after the SAIC review of the Work Packages and International Partners.

4.2.3. Analysis of Voyager as an SSF Analog.

Voyager was treated separately from other spacecraft because it is generally considered to represent the pinnacle of reliability achievement. The Jet Propulsion Laboratory provided SAIC with considerable help in obtaining and analyzing *Voyager* data, and their assistance is gratefully acknowledged. SAIC analyzed 27 *Voyager* anomaly reports and concluded 25 represented failures which, if they occurred on *Freedom*, would require EVA to repair. The number of equivalent ORUs was estimated by JPL and SAIC to be between 30 and 150 ORU equivalent units per *Voyager* spacecraft, with a mean of 75.6. Current exposure, or cumulative operating time, for *Voyager* is 12.5 years.

SSF - *Voyager* Equivalent Failure Calculations:

$$\frac{25\ \text{Failures}}{12.5\ \text{Years}} * \frac{3553\ \text{SSF ORU}}{75.6\ \textit{Voyager}\ \text{ORU}} = 94\ \text{Failures/Year}$$

It should be noted that five of the failures on *Voyager* occurred in type-4051 interface controllers, the only class "B" electronic part used on the spacecraft. All other electronic parts on *Voyager* were class "S". Additionally, all of the type-4051 failures were "cell" failures, and *Voyager* was designed so that individual cells could be programmed out of use. SAIC included all five type-4051 failures because we felt it unlikely that similar provisions would be made for like components in the current SSF design.

4.2.4. Analysis of NASA Goddard Satellites as an SSF Analog.

NASA Goddard provided SAIC with the Satellite Orbital Anomaly Report (SOAR) data base through May, 1990. The SOAR data base contained 410 anomaly reports covering 21 spacecraft. Of these, 2 satellites were not analyzed because of uncertainty as to their exposure. The 19 satellites studied represent a wide variety of mission and orbit types.

The majority of the anomaly reports provide unambiguous indication of whether a part or component "failed" in the sense that an equivalent "failure" aboard *Freedom* would require EVA to investigate or repair. Some cases required the SAIC analysts to make a determination based on their understanding of acceptable ORU performance on *Freedom*. In these cases an anomaly was considered a failure if it adversely affected the mission for a significant period of time or if it required major operational work-arounds. In the preliminary SAIC presentations not all of these anomalies were reflected and this created a discrepancy between Goddard and USAF satellite failure experience. This final report reflects a consistent standard used to evaluate satellite anomalies. One example of an ambiguous report is: "SCIENCE DATA STOPPED-ALL ZEROS IN DIGITL SCIENCE CHANNELS. ANALOG HOUSEKEEPING IS NORMAL. BEGAN OPERTG NORMLY 10/2. STOPPED AGAIN ON 10/14, STARTED 10/24. ... MAY BE DUE TO ELECTROSTATIC DISCHARGE ON SPACECRAFT OR COLD-SOLDER JOINT (POOR CONTACT) IN INSTRUMENT." Although this event cleared itself up, it had a significant mission impact and we assume an analogous event aboard *Freedom* would call for IVA/ground troubleshooting followed by an investigative EVA. It was therefore counted as a failure or EVA precipitator.

For each of the 19 satellites evaluated the number of failures and the exposure were entered into a CARP™ data base for aggregation. CARP™ (Computer Aggregation of Reliability Parameters) is a proprietary SAIC computer code for statistically combining failure data from a variety of sources while preserving confidence bounds. An independent evaluation of the suitability of CARP™ to this task is contained in Appendix K.

SAIC made three simplifying assumptions in performing the CARP™ aggregation. First, the failure rates were assumed to be lognormally distributed. This assumption is empirically justified by failure data from a wide variety of sources. Second, the satellites were equally weighted, or assumed to be equally appropriate generic surrogates for the Space Station. Finally, the variation in complexity among satellite types was ignored. This was justified since we are comparing the aggregate of all the satellites to the Space Station. Care was taken, however, to avoid comparing the gross failure rate results for several satellites without accounting for their relative complexity.

The CARP™ aggregate mean failure rate for Goddard satellites is $1.72*10^{-4}$ failures per hour, with a distribution error factor of 4.4. Table 4.9 shows the aggregation results from CARP™ in a tabular format. Figure 4.13 shows the information graphically.

The number of equivalent SSF ORUs per satellite was estimated using an informal Delphi technique and includes both NASA Goddard and USAF satellites. Our estimate was that a given satellite in this class contains between 10 and 60 equivalent SSF ORUs, with a mean of 28.4. This distribution is left-skewed because relatively simple satellites are more common than relatively complex satellites.

SSF - Goddard Satellite Equivalent Failure Calculations:

$$1.72*10^{-4} \text{ Failures/Hr} * \frac{3553 \text{ SSF ORU}}{28.4 \text{ Sat ORU}} = 0.022 \text{ Failures/Hr}$$

$$= 188.5 \text{ Failures/Year}$$

4.2.5. <u>Analysis of USAF Satellites as an SSF Analog.</u>

SAIC selected five USAF constellation-level programs to evaluate, representing a variety of mission types and altitudes. These programs were selected for availability of data (i.e., their historical anomaly records are unclassified), and because they incorporate a large body of recent satellite experience. Air Force Space Systems Division furnished SAIC with a subset of the Orbital Data Acquisition Program (ODAP) data base for this study. Additionally, the Rome Air Development Center / Reliability Analysis Center (RADC/RAC) provided more recent data for DSCS-III than is available in the ODAP data base.

Table 4.9.

CARP™ — DATA ANALYSIS DETAILED REPORT

Component Type Code: AA
Failure Mode Type Code: AA

Component Name: GODDARD SATELLITES
Failure Mode: RANDOM FAILURES

	D	MEAN	LOWER	MEDIAN	UPPER	EF
Plant-specific						
Interim aggregated		1.72-04	1.80-05	1.28-04	5.08-04	
Aggregated generic	L	1.72-04	2.58-05	1.14-04	5.08-04	4.4
Bayesian updated						
Final	L	1.72-04	2.58-05	1.14-04	5.08-04	4.4

PLANT-SPECIFIC DATA
Units (N for demands, H for hours, etc.): H
Number of failures:
Exposure (time or number of demands):

BAYESIAN UPDATING
Bayesian updating performed: N

FINAL
Final basis (P,G,B): G
Lognormal fitting method used: MN-EF

AGGREGATION DETAILS
Aggregation method (T,A,G): T
Weighting method (E,I,P,U,S): E

	MEAN	LOWER	MEDIAN	UPPER	EF	FAILURES	EXPOSURE	WEIGHT
1 AMPTE	1.62-04	7.60-05	1.49-04	2.93-04	2.0	8	49296	0.053
2 DE-1	1.19-04	5.87-05	1.10-04	2.07-04	1.9	9	75912	0.053
3 DE-2	5.95-04	2.79-04	5.47-04	1.07-03	2.0	8	13453	0.053
4 ERBS	2.29-04	1.23-04	2.16-04	3.79-04	1.8	11	48096	0.053
5 ISEE-1	6.92-05	2.77-05	6.15-05	1.37-04	2.2	6	86748	0.053
6 ISEE-3	5.88-05	2.36-05	5.23-05	1.16-04	2.2	6	102000	0.053
7 IUE	1.03-04	5.54-05	9.72-05	1.71-04	1.8	11	106752	0.053
8 LANDSAT-2	1.35-04	6.96-05	1.26-04	2.28-04	1.8	10	74343	0.053

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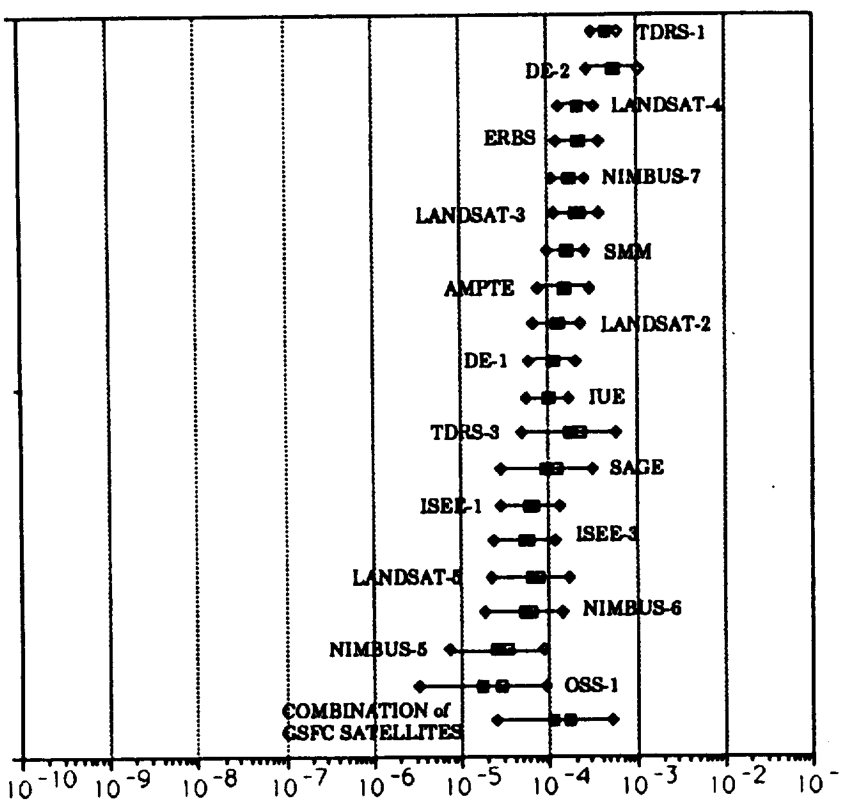
Table 4.9., Continued
CARP™ — DATA ANALYSIS DETAILED REPORT

Component Type Code: AA Component Name: GODDARD SATELLITES
Failure Mode Type Code: AA Failure Mode: RANDOM FAILURES

		MEAN	LOWER	MEDIAN	UPPER	EF	FAILURES	EXPOSURE	WEIGHT
9	LANDSAT-3	2.26-04	1.17-04	2.12-04	3.83-04	1.8	10	44292	0.053
10	LANDSAT-4	2.22-04	1.33-04	2.13-04	3.42-04	1.6	15	67536	0.053
11	LANDSAT-5	7.50-05	2.23-05	6.19-05	1.72-04	2.8	4	53328	0.053
12	NIMBUS-5	3.33-05	7.39-06	2.52-05	8.62-05	3.4	3	89981	0.053
13	NIMBUS-6	6.38-05	1.90-05	5.26-05	1.46-04	2.8	4	62724	0.053
14	NIMBUS-7	1.80-04	1.13-04	1.74-04	2.66-04	1.5	18	100248	0.053
15	OSS-1	2.84-05	3.30-06	1.72-05	8.95-05	5.2	2	70368	0.053
16	SAGE	1.25-04	2.77-05	9.45-05	3.23-04	3.4	3	24024	0.053
17	SMM	1.69-04	1.01-04	1.62-04	2.60-04	1.6	15	88776	0.053
18	TDRS-1	4.57-04	3.20-04	4.47-04	6.26-04	1.4	28	61296	0.053
19	TDRS-3	2.28-04	5.04-05	1.72-04	5.88-04	3.4	3	13176	0.053

Satellite Failure Rates From Goddard Space Flight Center



Failure Rate per Hour

Figure 4.13.

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The systems evaluated were: Defense Meteorological Satellite Program (DMSP); Defense Satellite Communications System (DSCS) II and III; Fleet Satellite Communications System (FLTSAT); and NAVSTAR Global Positioning System (GPS). DMSP is in a near Earth polar (sun-synchronous) orbit, and is (as the name implies) a weather observation system. DSCS-II, DSCS-III, and FLTSAT are geosynchronous communication satellites, and GPS is a navigation system in a 12 hour orbit.

We restricted the analysis to vehicles launched after November 1971 so that the components were roughly comparable to modern parts, and because pre-1972 data appeared somewhat unreliable. Additionally, the ODAP data base has not been consistently updated since mid-1988, so we curtailed our failure counts at May 1988, and truncated the exposures accordingly. This limited the number of DMSP satellites in the sample to 13, and the number of GPS satellites to 10. DSCS-III data from RAC is current, and the complete data set was used. For DMSP, failures of the Magnetic Tape Recorders and Scan Drive Mechanisms were not counted since there are no corresponding SSF ORUs and we felt that the large number of failures of these devices would unfairly bias the sample.

The basic analysis for equivalent SSF ORU failure rate was conducted in the same way the Goddard satellites were analyzed. In this case 1280 anomaly reports were reviewed, and a total of 433 failures were identified. The cumulative exposure for these USAF satellites was 1,596,874 hours, 182.3 years. The mean failure rate was $2.67 * 10^{-4}$ failures per hour, with a distribution error factor of 1.7. Table 4.10 shows the aggregation results from CARP™. As previously noted, the relative complexity of the spacecraft is not considered here, and different satellites should not be compared without keeping that in mind. The apparent difference between Goddard and USAF failure rates is due largely to a difference in overall complexity, but without detailed analysis beyond the scope of this study, any comparisons among the spacecraft should be avoided.

SSF - USAF Satellite Equivalent Failure Calculations:

$$2.67 * 10^{-4} \text{ Failures/Hr} \; * \; \frac{3553 \text{ SSF ORU}}{28.4 \text{ Sat ORU}} = 0.033 \text{ Failures/Hr}$$

$$= 292.6 \text{ Failures/Year}$$

Figure 4.14 shows the information graphically.

4.2.6. Analysis of *Mir / Salyut* as an SSF Analog.

Failure data for the *Mir* space station and associated *Salyut* docking module was supplied by Mr. James Oberg, author and expert on the Soviet space program. His estimates are based on failures which the

Table 4.10.

CARP™ — DATA ANALYSIS DETAILED REPORT

Component Type Code: AA
Failure Mode Type Code: AA
Component Name: USAF SATELLITES
Failure Mode: RANDOM FAILURES

	D	MEAN	LOWER	MEDIAN	UPPER	EF
Plant-specific						
Interim aggregated		2.94-04	1.71-04	2.75-04		4.75-04
Aggregated generic	L	2.94-04	1.64-04	2.79-04	4.75-04	1.7
Bayesian updated						
Final	L	2.94-04	1.64-04	2.79-04	4.75-04	1.7

PLANT-SPECIFIC DATA
Units (N for demands, H for hours, etc.): H
Number of failures:
Exposure (time or number of demands):

BAYESIAN UPDATING
Bayesian updating performed: N

FINAL
Final basis (P,G,B): G
Lognormal fitting method used: MN-EF

AGGREGATION DETAILS
Aggregation method (T,A,G): T Weighting method (E,I,P,U,S): U

	MEAN	LOWER	MEDIAN	UPPER	EF	FAILURES	EXPOSURE	WEIGHT
1								
DMSP						119	269555	0.236
	4.41-04	3.76-04	4.39-04	5.14-04	1.2			
Note: 13 SATELLITES, LAUNCHED AFTER 11/71								
2								
DSCS-II						118	525960	0.236
	2.24-04	1.91-04	2.23-04	2.61-04	1.2			
Note: 13 SATELLITES								
3								
DSCS-III						19	103731	0.055
	1.83-04	1.17-04	1.77-04	2.69-04	1.5			
Note: 3 SATELLITES								
4								
FLTSAT						51	264441	0.109
	1.93-04	1.49-04	1.91-04	2.44-04	1.3			
Note: 6 SATELLITES								
5								
GPS						126	433187	0.364
	2.91-04	2.49-04	2.90-04	3.37-04	1.2			
Note: 10 SATELLITES								

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USAF SATELLITES

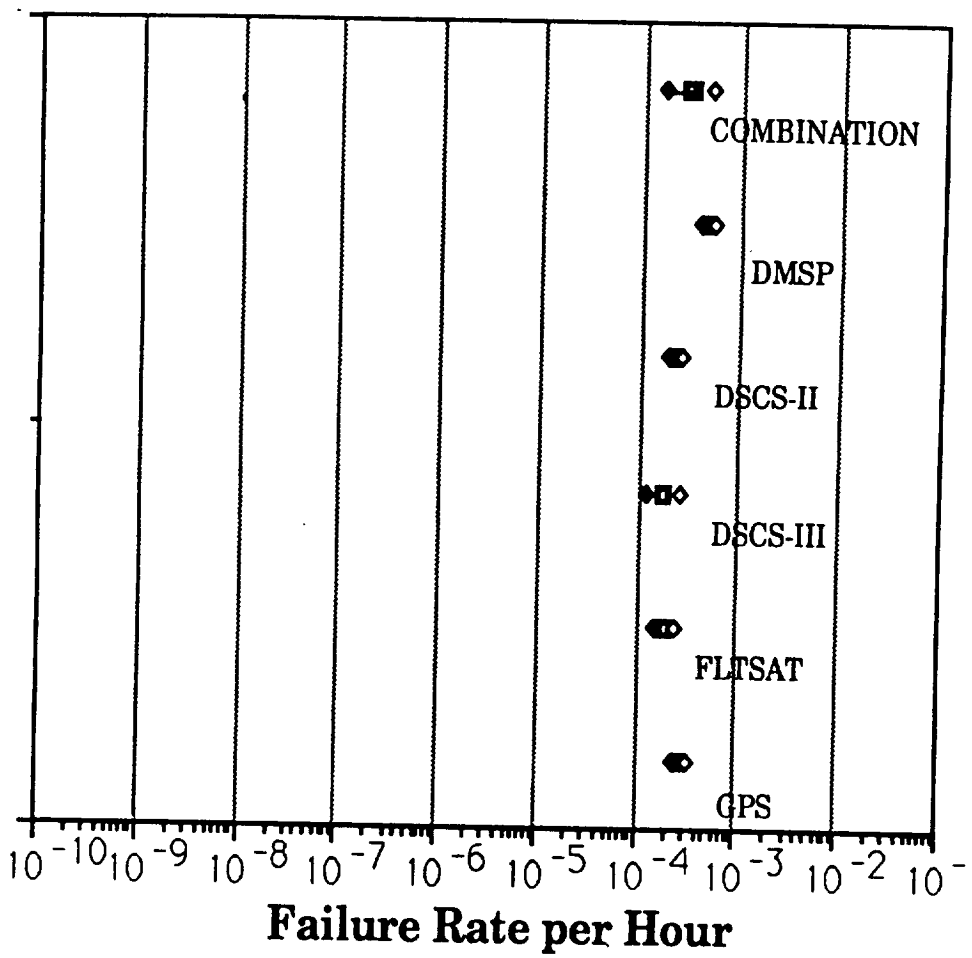

Figure 4.14.

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Soviets have acknowledged to him. This data is therefore less traceable than the other data presented here, but we felt it was important to provide the *Mir* analog in this analysis. We feel that Mr. Oberg's estimates are the best source available, but some *Mir* failures may be masked for a variety of reasons.

The estimated distribution of equivalent external SSF ORUs on *Mir* is from 12 to 106, with a "best guess" mean of 44. There have been 21 reported repairs, and the station has been in service from December 1977 through February 1990 (the last update on repairs), for an exposure of 12.167 years. The reported failure rate is therefore 1.7 failures per year, or $1.97*10^{-4}$ failures per hour.

SSF - *Mir / Salyut* Equivalent Failure Calculations:

$$1.97*10^{-4} \text{ Failures/Hr} * \frac{3553 \text{ SSF ORU}}{44 \text{ Mir ORU}} = 0.016 \text{ Failures/Hr}$$

$$= 139.4 \text{ Failures/Year}$$

4.2.7. Analysis of Space Shuttle as an SSF Analog.

SAIC conducted two independent analyses of Shuttle data. The first study used repair actions as the basis for estimating failure rates and was limited to post 51-L data. The second analysis used NASA Problem Reporting And Corrective Action (PRACA) data and covers 1982 through 1988. PRACA data from 1986 and 1987 was removed from the study after preliminary analysis since it was not representative of the operational system.

While there are minor internal discrepancies between the two Shuttle study methods, the numbers used were the best available to the analysts at the time they performed their studies. In keeping with the policy of not changing parameters after the results are in, we have elected not to reconcile these minor discrepancies.

4.2.7.1. SSF - Shuttle Analog Method 1, Repair Actions.

Data for the first Shuttle study was obtained from NASA Headquarters Code QT. Our goal in this study was to obtain the distribution of yearly failures one could expect on SSF external ORUs based on the Shuttle experience. We therefore made several assumptions to simplify the problem as much as possible. The first assumption was that the overall duty cycle for Shuttle components was roughly equivalent to the overall duty cycle for SSF components. The calender time for which we had data was therefore used to determine Shuttle component exposure, and no attempt was made to separate flight, test, refit, and storage exposures. The second simplifying assumption was that all Shuttle systems were fair analogs to Space Station except Propulsion Systems and Flight Control Hydraulic Systems.

The unit part for the first Shuttle study was the "Replaceable Unit (RU)", generally one level of complexity lower than a Line Replaceable Unit (LRU) or ORU. The number of RUs on Shuttle is 52900, of which 4000 are in the propulsion or flight control hydraulic systems. There are therefore 48900 SSF analog RUs on Shuttle. The number of RUs on *Freedom*, found in the *SSF System Design Tradeoff Model, Rev. B, Release 1.2, September 1989*, is 73448. Over a 2 year period there were 2422 RU repairs or replacements on systems other than propulsion or hydraulics, on 3 orbiters. The total exposure was therefore 6 orbiter years. Finally, the fraction of external RUs is assumed to be equal to the fraction of external ORUs, 5700/20000 = 0.285.

SSF - Shuttle Equivalent Failure Calculations - Method 1:

$$\frac{2422 \text{ Failures}}{6 \text{ Years}} * \frac{73448 \text{ SSF RU}}{48900 \text{ STS RU}} * \frac{5700 \text{ EXT}}{20000 \text{ TOTAL}} = 172.8 \text{ Failures/Yr}$$

$$= 0.0197 \text{ Failures/Hr}$$

4.2.7.2. SSF - Shuttle Analog Method 2, PRACA Data.

As with each of the other in-service studies, the objective in this study was to estimate a distribution of SSF external ORU failure rates using experiential data. In this case Shuttle Problem Reporting and Corrective Action (PRACA) data was broken down by orbiter subsystem, and 13 subsystems were found to be substantially similar to SSF subsystems. For each of the 13 like subsystems, the number of PRACA reports per year per subsystem was counted. SAIC estimated that 10% of the PRACA reports were "hard" failures, which would require removal/replacement on Space Station. Using this criterion we arrived at an explicit distribution of orbiter failure rates ranging from 0.7 failures per year for the Thermal Control System to a high of 20.2 failures per year for the orbiter Data Processing System. The mean and median of this explicit distribution were readily calculated, the mean being 8.1 failures/year, and the median at 5.7 failures/year.

We then scaled the explicit range of failure rates to SSF by estimating that there are 18,000 total ORUs on Space Station, 6000 orbiter LRUs/ORUs, of which approximately 1/3 are external ORUs. Since (18000/6000)*1/3 = 1, the distribution of SSF ORU failures per subsystem is the same as the distribution above. SAIC estimated the number of subsystems to be 30, so the distribution of SSF external ORU failure rates from PRACA data is:

SSF - Shuttle Equivalent Failure Distribution - Method 2:

MEAN	=	243 failures/year	$=2.77*10^{-2}$/hour
LOW	=	21 failures/year	$=2.40*10^{-3}$/hour
MEDIAN	=	171 failures/year	$=1.95*10^{-2}$/hour
HIGH	=	600 failures/year	$=6.85*10^{-2}$/hour

It is interesting to note that this distribution, which was explicitly derived from data, is a close match in shape to the lognormal distributions assumed for each of the other in-service estimates.

Figure 4.15 shows the distribution of PRACA reports by subsystem.

Figure 4.16 summarizes the Shuttle failure experience and analysis results.

4.2.8. Analysis of *Skylab* as an SSF Analog.

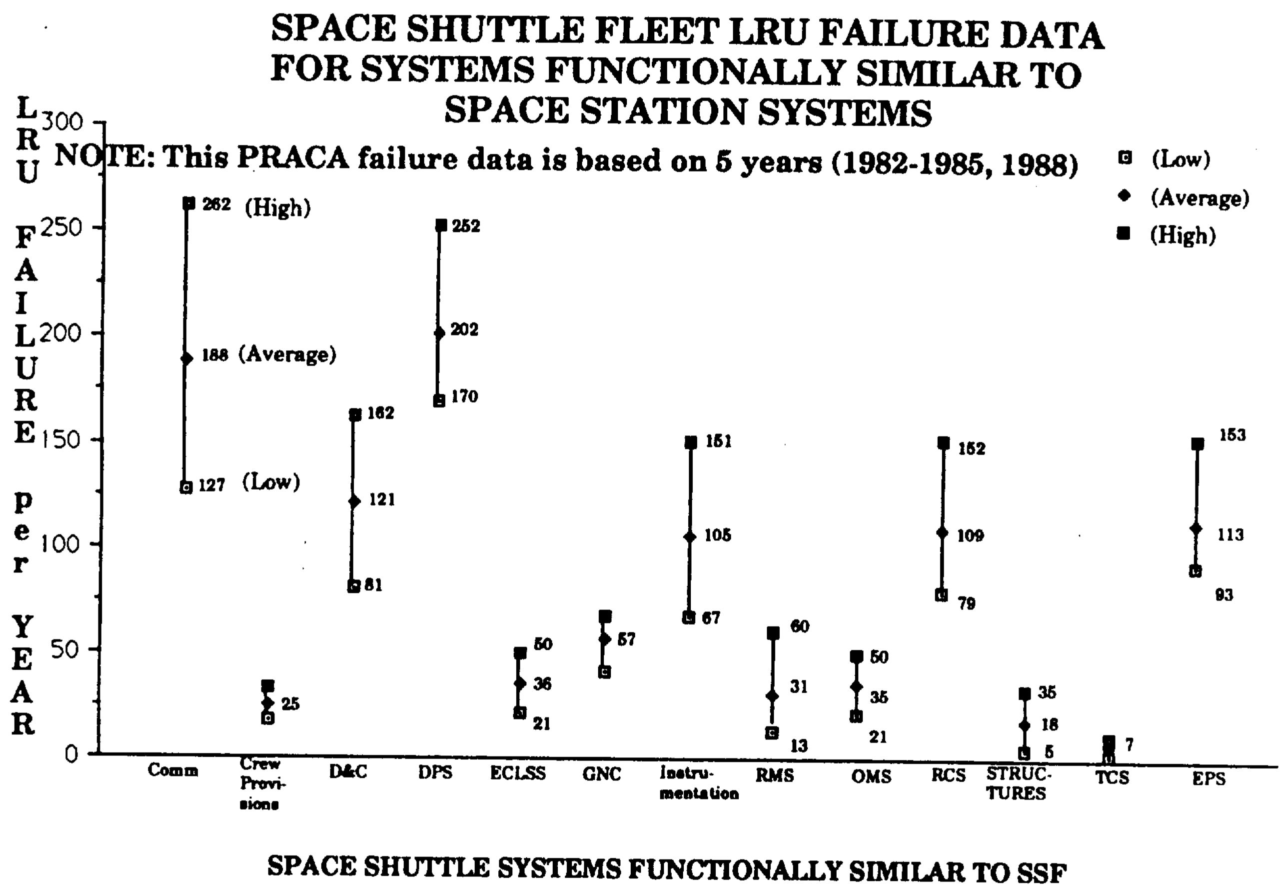
Skylab failure data came from the Marshal Space Flight Center *Skylab Mission Report*, NASA TM X-64814, Oct. 1974. Experiential data from astronauts and Mission Operations Directorate personnel was also considered, especially in estimating the number of equivalent external ORUs.

Mission histories indicate that corrective maintenance was the primary purpose for 5 of the 10 EVAs performed from *Skylab*. The number of SSF equivalent ORUs on *Skylab* is estimated to be between 10 and 100, with a mean of 50, and *Skylab* was in operation for a total of 6 months. The equivalent failure rates for Space Station *Freedom* are from 73 per year to 730 per year, with a mean of 385 per year.

4.2.9. Analysis of Trident Submarines as an SSF Analog.

Naval Sea Systems Command provided SAIC with the current USS *Ohio* Integrated Logistics Support Effectiveness Assessment System (ILS/EA) data base for this study. Their support of the EMTT effort is appreciated.

SAIC elected not to consider propulsion plant components in this study. We felt that the non-propulsion components represented a closer SSF analog, and including propulsion components would have biased the component mixture away from a fair Space Station comparison. From *Trident ICS/EAS Catalog of Reports*, NAVSEA T9080-AC-CAT-010 there are 28,850 non-propulsion components aboard. From the ILS/EA we obtained the cumulative service life or exposure of 10 years, and the number



SPACE SHUTTLE FLEET LRU FAILURE DATA
FOR SYSTEMS FUNCTIONALLY SIMILAR TO
SPACE STATION SYSTEMS
NOTE: This PRACA failure data is based on 5 years (1982-1985, 1988)
(Low)
(Average)
(High)
LRU FAILURE per YEAR
300
250
200
150
100
50
0
262 (High)
188 (Average)
127 (Low)
25
162
121
81
252
202
170
50
36
21
57
151
105
67
60
31
13
50
35
21
152
109
79
35
18
5
7
153
113
93
Comm
Crew Provi-sions
D&C
DPS
ECLSS
GNC
Instru-mentation
RMS
OMS
RCS
STRUC-TURES
TCS
EPS
SPACE SHUTTLE SYSTEMS FUNCTIONALLY SIMILAR TO SSF

Figure 4.15.

SPACE STATION FAILURE RATE ESTIMATE - METHOD TWO

OBJECTIVE: Estimate a RANGE of SSF External ORU failure rates, based on PRACA data, for the Orbiter Program for Subsystems functionally similiar to Space Station Freedom.

- 13 orbiter systems found to be significantly similiar to SSF systems
- Average LRU failures per year were estimated from Orbiter PRACA data for each of the applicable Orbiter subsystems.
- The average PRACA *failures/year/subsystem* ranges from a low of 7 for the Thermal Control System to a high of 202 for the Data Processing System.
- Assumed 10% of PRACA reports are "hard" failures, which yields a LOW of 0.7 and a HIGH of 20 *failures/year/subsystem.*
- Estimated SSF Scaling Factor =

$$\frac{\text{18000 Estimated ORUs in SSF}}{\text{6000 Applicable Orbiter Subsystem LRUs}} \times \frac{1}{3} \text{ of SSF ORUs}$$

(assumed $\frac{1}{3}$ of SSF ORUs to be external)

- Assumed 30 equivalent SSF subsystems = 1 SSF Scaling Factor

The Range of SSF External ORU Failure Rates based on Orbiter Subsystems functionally similar to SSF Subsystems are estimated to be :

LOW = 0.7 failures/year/subsystem x Scaling Factor of 1 x 30 SSF Subsystems = 21 failures/year
AVERAGE = 8.1 failures/year/subsystem x Scaling Factor of 1 x 30 SSF Subsystems = 243 failures/year
HIGH = 20 failures/year/subsystem x Scaling Factor of 1 x 30 SSF Subsystems = 600 failures/year
MEDIAN = 5.7 failures/year/subsystem x Scaling Factor of 1 x 30 SSF Subsystems = 171 failures /year

Figure 4.16.

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of corrective maintenance actions performed was 7648. Based on the submarine experience of several analysts and our familiarity with basic ORU design we estimated that there was a one-to-one correspondence in complexity between a shipboard component and an SSF ORU.

SSF - Trident Equivalent Failure Calculations:

$$\frac{7648 \text{ Failures}}{10 \text{ Years}} * \frac{3553 \text{ SSF ORU}}{28850 \text{ Trident ORU}} = 94.2 \text{ Failures/Year}$$

$$= 1.08*10^{-2} \text{ Failures/Hr}$$

The implication of these calculations is that a Trident submarine is as reliable as *Voyager*. This conclusion, however, must be tempered by an understanding of the submarine preventive maintenance philosophy, discussed below. **If preventive maintenance actions are counted along with corrective maintenance actions, the equivalent SSF failure rates are:**

176 Failures/Year $\quad$ $2.00*10^{-2}$ Failures/Hr

Nuclear submarines have several features in common with the Space Station, despite obvious differences. Notable similarities include the following:

Many of the same functional systems.
Internal environment (pressure boundary surrounded by a hostile medium).
Long periods of isolation from resupply.
Design for high reliability.
Design for approximately a 30 year life.
Design for modular replacement.
The presence of a crew.
Limited on-board diagnosis and repair capability.
Limited on-board spares capacity.

These similarities suggest that nuclear submarine experience might be a reasonable predictor of Space Station reliability, and that a consideration of submarine design and operating principles could be helpful to the Space Station program. One aspect of submarine operations is particularly important to understanding the limitations of the failure rate / maintenance analogy presented here. The failure analog we have developed here is based on the corrective maintenance actions alone. But on a submarine, nearly half the maintenance actions are planned, and 80% of maintenance manpower is devoted to planned (preventive) maintenance. To achieve the failure rate indicated by this analog would require that an enormous effort be placed in preventive maintenance, and understanding the preventive maintenance trades may well be a necessary hurdle before the Space Station can achieve acceptable maintenance loads.

4.2.10. Summary.

Table 4.11 and Figure 4.17 show the results of a CARP™ aggregation of the failure experience from each of the 73 Space Station *Freedom* surrogates analyzed. A remarkably consistent picture of failure experience in modern high reliability systems is observed. These results show that if Space Station *Freedom*: (1) is similar in component reliability to existing systems, and (2) has approximately 3553 external ORUs, then the expected external failure rates will be:

Mean:	$2.38*10^{-2}$ Failures per Hr;	208 per Year.
Lower:	$5.88*10^{-3}$ Failures per Hr;	52 per Year.
Median:	$1.86*10^{-2}$ Failures per Hr;	163 per Year.
Upper:	$5.89*10^{-2}$ Failures per Hr;	516 per Year.

Figure 4.18 summarizes the in-service experience by showing what the expected external ORU failure rate on Space Station *Freedom* would be if it were built like each of the analogs.

Figure 4.19 puts the overall failure rate of Space Station *Freedom* external ORUs in persepctive. A goal of one maintenance-related EVA per month has been advanced as a realistic target for the Space Station. With approximately 3553 non-structural external ORUs, and assuming one EVA per failure, this translates to a target mean per-ORU failure rate of about 3.9×10^{-7} failures per hour.

Now consider the experience of the two *Voyager* planetary probes, whose random failure rate per "equivalent ORU" was approximately 3×10^{-6} per hour. Considering random failures only, Space Station external ORUs will thus have to achieve a per-unit reliability 7.8 times better than that experienced by the most reliable spacecraft ever flown in order to meet the one-EVA-per-month target. The disparity between the target and *Voyager* experience widens further if we add EVAs for end-of-life replacements and account for the differences between *Freedom's* LEO environment and the relatively benign deep-space environment of *Voyager*.

Because of the wide range of technologies used, an eight-fold improvement in the mean reliability of the whole external ORU complement would require coincident reliability breakthroughs in multiple technologies, a very unlikely contingency between now and 1995. Thus a comparison with *Voyager* in-service experience demonstrates that an average Space Station maintenance EVA frequency of one per month is beyond the bounds of current technology with the baseline Station configuration and maintenance philosophy.

Table 4.11.

CARP™ — DATA ANALYSIS DETAILED REPORT

Component Type Code: AA   Component Name: IN-SERVICE RESULTS
Failure Mode Type Code: AA   Failure Mode: ADJUSTED TO SSF COMPLEXITY

	D	MEAN	LOWER	MEDIAN	UPPER	EF
Plant-specific						
Interim aggregated		2.38-02	8.25-03	1.81-02	5.89-02	
Aggregated generic	L	2.38-02	5.88-03	1.86-02	5.89-02	3.2
Bayesian updated						
Final	L	2.38-02	5.88-03	1.86-02	5.89-02	3.2

PLANT-SPECIFIC DATA

Units (N for demands, H for hours, etc.): H
Number of failures:
Exposure (time or number of demands):

BAYESIAN UPDATING

Bayesian updating performed: N

FINAL

Final basis (P,G,B): G
Lognormal fitting method used: MN-EF

AGGREGATION DETAILS

Aggregation method (T,A,G): T   Weighting method (E,I,P,U,S): E

	MEAN	LOWER	MEDIAN	UPPER	EF	FAILURES	EXPOSURE	WEIGHT
1								
Goddard Sats	2.20-2	-	-	-	4.4			0.125
	2.20-02	3.48-03	1.53-02	6.75-02	4.4			
Note: Aggregate distribution from CARP of 19 Satellites								
2								
Mir	1.60-2			1.3				0.125
	1.60-02	1.29-02	1.68-02	2.18-02	1.3			
Note: Derived distribution from Failures and Exposure								
3								
Shuttle-M1	1.97-2			1.2				0.125
	1.97-02	1.63-02	1.96-02	2.35-02	1.2			
Note: Derived distribution from Failures and Exposure								
4								
Shuttle-M2	2.77-2	2.40-3	1.95-2	6.85-2				0.125
	2.77-02	6.87-03	2.17-02	6.85-02	3.2			
Note: Explicite distribution from PRACA data.								
5								
Skylab	4.39-2				2.4			0.125
	4.39-02	1.59-02	3.81-02	9.14-02	2.4			
Note: Derived distribution based on Failures and Exposure								
6								
Submarine	1.08-2				1.2			0.125
	1.08-02	9.52-03	1.14-02	1.37-02	1.2			
Note: Derived distribution based on Failures and Exposure								

Table 4.11., Continued

CARP™ — DATA ANALYSIS DETAILED REPORT

Component Type Code: AA Component Name: IN-SERVICE RESULTS
Failure Mode Type Code: AA Failure Mode: ADJUSTED TO SSF COMPLEXITY

	MEAN	LOWER	MEDIAN	UPPER	EF	FAILURES	EXPOSURE	WEIGHT
7								
USAF Sats	3.30-2	-	-	-	1.7			0.125
	3.30-02	2.01-02	3.42-02	5.81-02	1.7			
Note: Aggregrate distribution from CARP of 45 Satellites								
8								
Voyager	1.07-2				1.4			0.125
	1.07-02	8.04-03	1.13-02	1.58-02	1.4			
Note: Derived distribution from Failures and Exposure.								

IN-SERVICE RESULTS

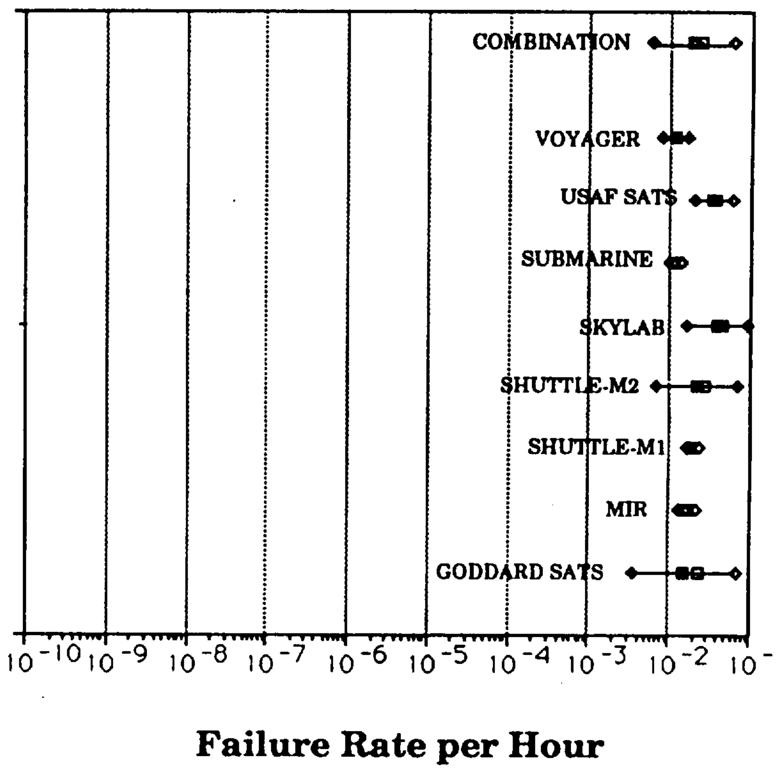


Figure 4.17.

Configuration 1/1/90 - SPACE STATION FREEDOM
EXTERNAL ORU
FAILURE FREQUENCY COMPARISONS
[RANDOM FAILURES ONLY]

		IF SSF WERE BUILT LIKE...	THE EXPECTED NUMBER OF FAILURES WOULD BE... PER MONTH	PER YEAR
HISTORICAL EXPERIENCE	UNMANNED SPACECRAFT	VOYAGER - DEEP SPACE PROBES	7.8	94
		NASA/GODDARD SATELLITE	15.7	188
		AIR FORCE SATELLITE	24.4	293
	MANNED SPACECRAFT	SALYUT/MIR*	11.6	139
		SPACE SHUTTLE	17.4	209
		SKYLAB	32.1	385
	OTHER	NEW FBM SUBMARINES	7.8	94
ESTIMATES		SYNTHESIZED TECHNOLOGY	27.4	329
		WORK PACKAGE DESIGNERS	14.3 (12.1)**	171 (145)**
		HUBBLE SPACE TELESCOPE	11.3	135

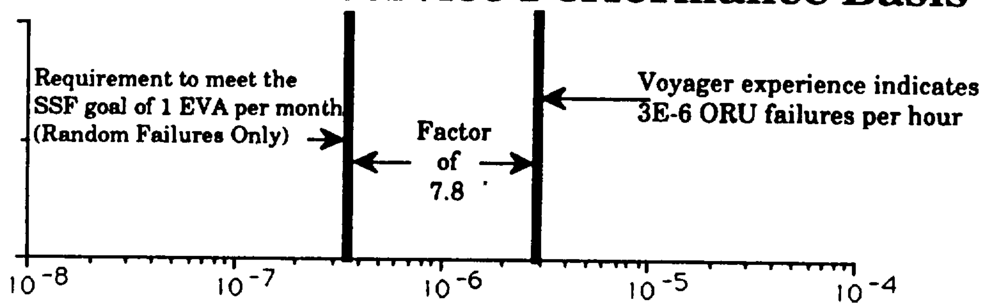
*Acknowledged failures

**Based on latest update of SAIC Data Base (6/15/90)

Figure 4.18.

SAIC EMTT

Comparison of the SSF EVA Goal on a 'Best ORU' In-Service Performance Basis



Failure Rate per Hour

Implication: SSF would have to perform 7.8 times better than the 'best' operational equipment found in this study in order to meet the above requirement.

Assumption: 1 EVA per ORU Failure

Figure 4.19.

4.3. Random Failure Results Comparison.

As can be seen from the individual comparisons in the synthesis approach, the individual experts while differing in their estimates produced mean estimates which were very close in most cases and within an order of magnitude in all cases. However, there were reasonable diferences in the range of their estimates. This result is consistent with the concept that their estimates were derived from an independent experience perspective of the same problem. The result provides further credibility to the approach and to the concept that the aggregated result of the experts' judgments should better represent the problem they were estimating. When the aggregated estimates are compared with the estimates made for the Hubble Space Telescope, they compare remarkably well for both for the electrical and electromechanical ORUs, but not so well for the mechanical ORUs. The mechanical disparity is better understood when it is remembered that only a single ORU was classified in this class for Hubble.

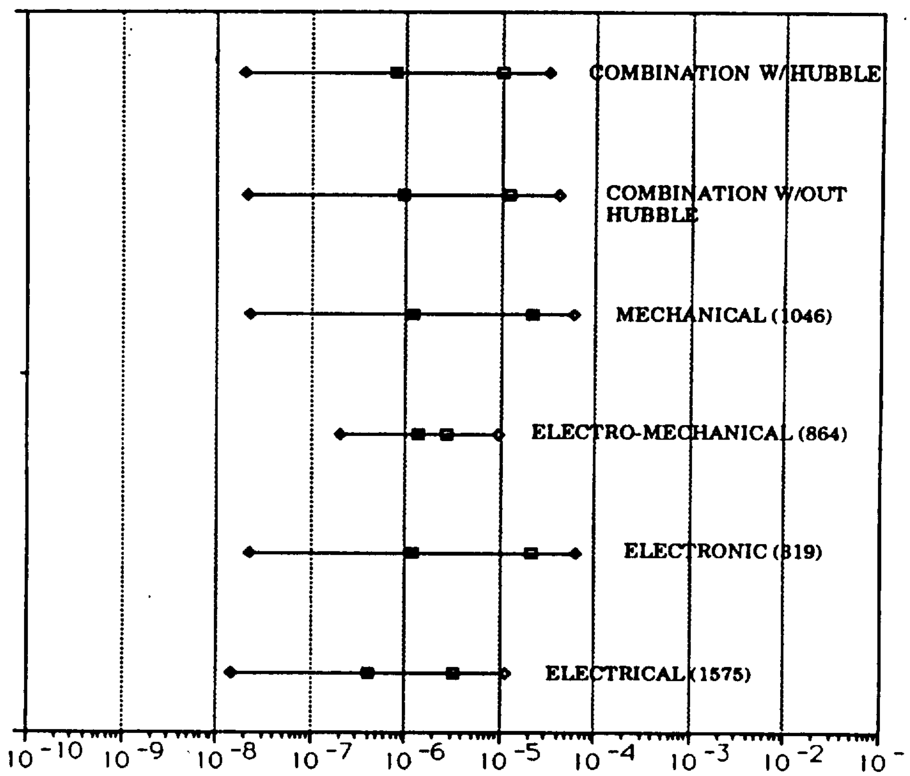
The general agreement provides assurance that not only does the synthesis process produce reasonable results for hypothetically constructed ORUs, but also that these results will remain reasonable when compared with the actual ORUs of a particular spacecraft provided there is a sufficient population of ORUs in each class such that the concept of a distribution of ORU failure rates is viable.

When the individual ORU type distributions are weighted by populations representative of those on SSF and aggregated into a mixture representative of the entire SSF ORU complement as is shown in Figure 4. 20 it can be seen that the addition or deletion of the HST case to the synthesis process barely changes the mean and barely shifts the resulting distribution. This result also confirms the consistency of the synthesis analysis with the independently derived MSFC/HST analysis.

When the in-service spacecraft estimates are compared with data derived from an *Ohio* Class Fleet Ballistic Missile (FBM) submarine, the mean failure rates compare remakably well. (The remarkable comparison in the range of the estimate is an artifact of the analysis because no distribution could be derived from the single estimate for the FBM). When these estimates are compared with the final synthesis estimates it should be noted that the means of the estimates correspond reasonably well and that the in-service estimate ranges are within the synthesis bounds. These results are consistent with the hypothesis that the in-service estimates are actual instances of the hypothetical distribution of synthesized ORUs derived from the same technological base.

Finally, SAIC derived a failure rate estimate from Work Package and International Partner data which became available much later. It was generated, as discussed in Section 5, from an average tabulation of the individual ORU failure rate estimates. The Work Package / International Partner estimate is compared with the in-service and synthesis estimates in Figure 4.21. As can be seen this estimate is consistent with the range and mean values of the other two estimates although a bit more optimistic.

SYNTHESIS APPROACH FAILURE DATA SUMMARY
(Weighted by SSF ORU Population)



Failure Rate per Hour

Figure 4.20.

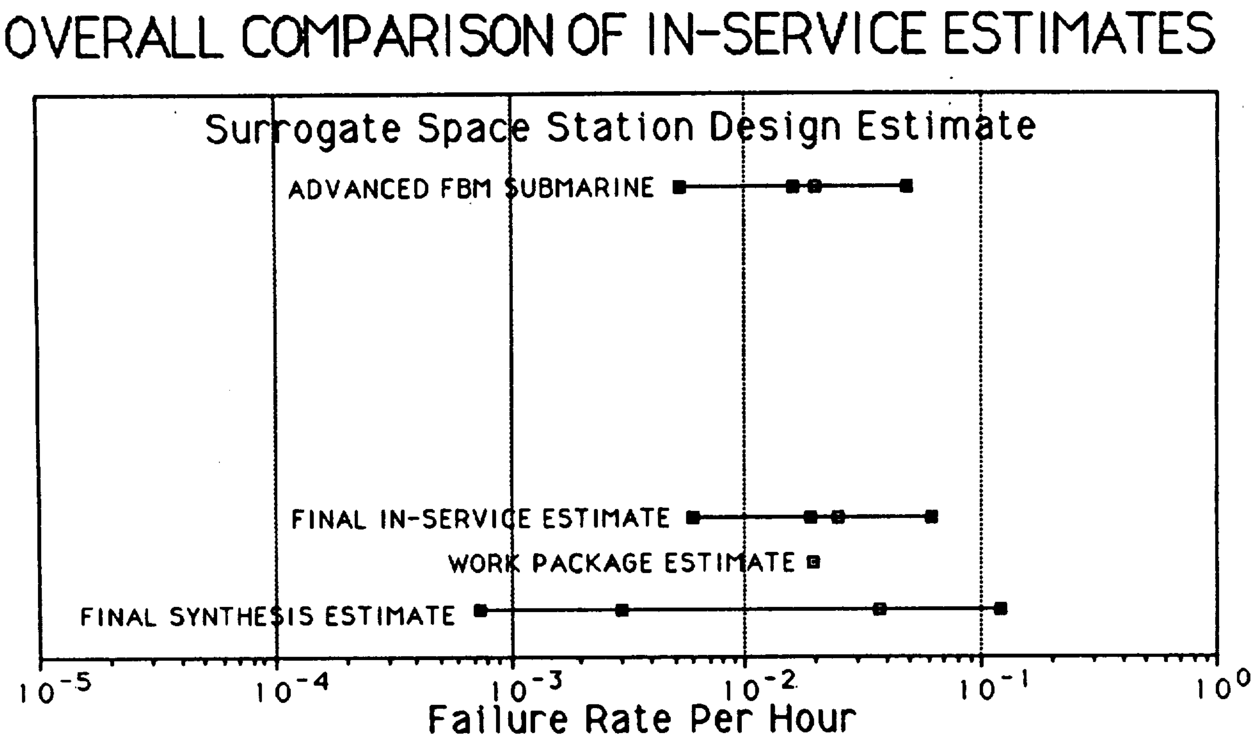

OVERALL COMPARISON OF IN-SERVICE ESTIMATES
Surrogate Space Station Design Estimate
ADVANCED FBM SUBMARINE
FINAL IN-SERVICE ESTIMATE
WORK PACKAGE ESTIMATE
FINAL SYNTHESIS ESTIMATE
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Failure Rate Per Hour

Figure 4.21.

5.0. ANALYSIS OF DATA FROM WORK PACKAGES AND INTERNATIONAL PARTNERS.

5.1. Summary of Approach.

Much of the Space Station *Freedom* Reliability Data Analysis was based on the external ORU reliability data furnished by the various Space Station Work Packages and International Partners (WP/IPs), or by their contractors. In order to confirm the validity of this information (or in few instances, to supplement or correct it), SAIC independently audited and updated the information the ORU design organizations submitted to the EMTT. We then performed a series of reliability data analyses on the resulting SAIC data base. This section briefly summarizes the updating, auditing, and analysis processes; sections 5.2 through 5.7 describe these processes and their results in detail.

5.1.1. Data Audit and Update Process.

5.1.1.1. Objectives.

The objectives of the data audit and update process were the following:

- Update and finalize the ORU reliability data, including random failure rates, life limits, type definitions, boundary definitions, and inventories.
- Develop separate random failure rates and life limits for life-limited ORUs so these two elements can be modeled separately.
- Determine and record the "pedigree," i.e. the underlying data sources and analytical methodology, of the ORU reliability data.
- Assess and where necessary, correct the analytical methodology.
- Determine, if possible, the statistical uncertainty of the ORU failure rates.
- Evaluate the "engineering tolerance" of reliability data developed from analysis of the history of analogous hardware, i.e., how closely the analyzed equipment compares to actual *Freedom* external ORUs.
- Identify the key ORU reliability drivers, i.e., the technical, application, and environmental characteristics, key components, etc. which dominate the reliability of each ORU.

- Resolve any WP/IP reliability data whose credibility is considered questionable through discussions with the WP/IP reliability and design engineers, if possible; otherwise, develop more representative reliability information to supplement or replace the questionable data.

- Create an auditable set of records of the data analysis.

5.1.1.2. Data Acquisition, Update, and Audit Process.

The Space Station external ORU set will be procured in seven distinct "work packages," each of which is under the supervision of either a NASA center or an international-partner space agency. Each work package involves one or more prime contractors, each typically with several major subcontractors. This complex program structure made auditing and updating the WP/IP reliability data a time-consuming yet essential task. The technique involved the following steps, many of which were performed in parallel in order to meet NASA's aggressive schedule.

(1) We designed a data base structure and developed data base management application software for the independent SAIC data base.

(2) We imported relevant data from the EMTT data base maintained by Ocean Systems Engineering into the SAIC data base.

(3) We identified the contact person(s) at each WP/IP (or prime contractor) who was assigned to be responsible for supporting the data audit and update.

(4) We developed a list of reliability, design, and environmental information and other WP/IP resources required to support the objectives listed in the previous section, and transmitted it to the WP/IP contacts. In summary, we requested the following:

<u>ORU data</u>:

Name (unique identifier)
Function
Principal reliability drivers
Parts inventory
Interactions with other ORUs
Internal redundancy
Duty cycle
Population

Random failure rate estimation information (for all ORUs):

Description of estimation process
Major physical processes affecting failure rate
Major operational factors affecting failure rate
Best average failure rate
Major underlying assumptions of failure rate estimate

Life limit estimation information (for life-limited ORUs):

Life limit time
Uncertainty in degradation rate
Degradation mechanism
Degradation effect
Factors affecting degradation rate
Degradation monitoring approach
End-of-life criteria

(5) Where practical, an SAIC data acquisition team visited the WP/IP site where the requested information was most conveniently available (either a NASA center or a prime contractor facility) in order to collect the requested data, investigate its pedigree, and generally clarify any questionable areas in line with the objectives of the update and audit process. (If a visit was impractical within the short time frame of the study, we attempted to accomplish the same purposes by correspondence and telephone. However, this was only done for the ESA and NASDA International Partners.)

(6) We incorporated the audited and updated information into the independent SAIC data base.

5.1.2. Reliability Data Analysis.

The analysis of the audited and updated WP/IP external ORU reliability data involved the following- steps:

(1) SAIC compared the realism of the random failure rates estimated by the WP/IPs with the bounds of reasonableness for the applicable ORU type which we developed in the in-service and synthesis analyses. In the few instances where the WP/IP either failed to supply information or we considered the WP/IP failure rates unrealistic, we substituted more representative failure rates for similar hardware and environmental conditions supplied by another WP/IP.

(SAIC did not attempt ot evaluate the realism of the WP/IP life estimates for life-limited ORUs or to supply "better" estimates. Life estimates are fundamentally a design issue, and the SAIC team was not technically qualified to substitute its judgement for that of the ORU designers in this area.)

(2) We used the SAIC data base management software system to perform a series of sorts, summations, and simulations on the audited and updated ORU populations, random failure rates, and WP/IP life limits in the data base. This provided such products as a total lifetime failure prediction for all external ORUs, a ranking of ORUs by their contribution to maintenance actions over the life of the Station, and a mean failure rate for all Freedom external ORUs.

5.2. Results of Review and Audit of Data.

As discussed in the previous section, SAIC conducted a thorough review and audit of the external ORU reliability data submitted by the Space Station Work Packages, International Partners (WP/IPs), and their contractors. This section summarizes the results of the review of each WP/IP, together with some general information about the work package, intended to put the data review in perspective. A general evaluation of the methodology used to develop the WP/IP reliability estimates follows the individual WP/IP review results in section 5.2.8. (The complete SAIC external ORU reliability data base containing the updated and audited data is reproduced in section 5.3.)

5.2.1. Work Package 1.

(1) Responsible NASA center or international partner agency: NASA Marshall Space Flight Center.

(2) Scope of supply: US pressurized modules.

(3) Principal contractor(s): Boeing.

(4) Analytical approach: for random failures, ranked both external and internal ORU failure rates by engineering judgment; anchored these rates to space-based generic data (NPRD-3) where close analogs exist; extrapolated rates for ORUs between anchor points.

(5) Evaluation of the approach: reasonable given the immaturity of the design.

(6) Changes in ORU inventory and reliability data from EMTT submittal: not significant.

(7) Principal maintenance drivers:

(a) 10-year life limit of micrometeoroid/debris (M/D) shields, due to erosion of the white-painted surface and resulting loss of thermal reflectivity.

(b) 10-year life limit of exposed multi-layer thermal insulation (MLI) atributable to surface degradation by ultraviolet (UV) and atomic oxygen (AO).

(8) Design changes planned to deal with these items:

(a) An anodized surface substituted for painted M/D shield surface and possibly thicker material in susceptible areas, expected to increase shield life to more than 15 years.

(b) Exposed MLI to be covered with M/D shielding to exclude UV and AO, increasing life to 30 years or more, but adding more M/D shields.

(9) Other major reliability design issues:

(a) Undefined life expectancy of seals in windows and between modules.

(b) Possible leakage of numerous quick-disconnects in fluid systems.

5.2.2. Work Package 2.

(1) Responsible NASA center or international partner agency: NASA Johnson Space Flight Center.

(2) Scope of supply: Main Station infrastructure except for pressurized modules and electrical power system.

(3) Principal contractor(s): McDonnell-Douglas.

(4) Analytical approach: Bottom-up parts count using MIL-HDBK-217E and NPRD-3 generic data plus some subcontractor estimates.

(5) Evaluation of the approach: reasonable given the immaturity of the design.

(6) Changes in ORU inventory and reliability data from EMTT submittal: Some due to design refinements, analytical improvements, and correction of errors, but not enough to significantly affect the results of the study.

(7) Principal maintenance drivers:

(a) Random failures of numerous and complex digital data multiplexer-demultiplexers (MDMs).

(b) Random failures of numerous valves.

(c) Random failures of numerous fluid quick-disconnects.

(d) Random failures and life limits of TV cameras and lights.

(8) Design changes planned to deal with these items: None currently in progress.

(9) Other major reliability design issues:

(a) Uncertain life expectancy of rotary ammonia coolant joint.

(b) Degration of lubricants exposed to AO.

(c) Degradation of graphite structural members due to debris impingement and AO.

5.2.3. Work Package 3.

(1) Responsible NASA center or international partner agency: NASA Goddard Research Center.

(2) Scope of supply: Flight Telerobotic Services (FTS), Attached Payload Accommodation Equipment (APAE).

(3) Principal contractor(s): Martin Marietta (FTS), General Electric (APAE).

(4) Analytical approach: Bottom-up parts count using MIL-HDBK-217E and NPRD-3 generic data plus some subcontractor estimates.

(5) Evaluation of the approach: reasonable given the immaturity of the design.

(6) Changes in ORU inventory and reliability data from EMTT submittal: Some due to design refinements and analytical improvements but not enough to significantly affect the results of the study.

(7) Principal maintenance drivers:

(a) Life limits of FTS lamps.

(b) Life limits of FTS cameras.

(c) Life limits of APAE thermal coatings.

(d) Life limits of FTS batteries.

(8) Design changes planned to deal with these items: None currently in progress.

(9) Other major reliability design issues: AO degradation of exposed lubricants at articulated joints of FTS.

5.2.4. Work Package 4.

(1) Responsible NASA center or international partner agency: NASA Lewis Research Center.

(2) Scope of supply: Electrical power generation and distribution system.

(3) Principal contractor(s): Rocketdyne Div. of Rockwell International (prime WP contractor, supplying power components except for PV arrays and batteries); Lockheed (photovoltaic arrays); Ford Aerospace (batteries).

(4) Analytical approach: Bottom-up parts count using MIL-HDBK-217E and NPRD-3 generic data plus some subcontractor life-test and historical data.

(5) Evaluation of the approach: reasonable given the immaturity of the design.

(6) Changes in ORU inventory and reliability data from EMTT submittal: some due to design refinements but not enough to significantly affect the results of the study.

(7) Principal maintenance drivers:

(a) 15-year life limit of power cable sets.

(b) Random failures of data interfaces.

(c) 15-year life of photovoltaic arrays.

(8) Design changes planned to deal with these items: none currently in progress.

(9) Other major reliability design issues:

(a) Flexible PV arrays ("blankets") consist of silicon PV cells bonded to multi-layer Kapton substrate. If not protected, the substrate will be rapidly degraded by AO and UV. This may not have been considered in the PV blanket life estimate.

(b) AO degradation of exposed lubricants at gimbals.

(c) Potential leakage of numerous fluid quick disconnects in thermal control subsystem.

(d) Contact life of electromagnetic contactors in remote power controllers (RPCs).

5.2.5. Japan Experiment Module (JEM).

(1) Responsible NASA center or international partner agency: National Space Development Agency of Japan (NASDA).

(2) Scope of supply: JEM pressurized module and auxiliaries.

(3) Principal contractor(s): not available.

(4) Analytical approach: various, including bottom-up parts count using MIL- HDBK-217E and NPRD-3 generic data, subcontractor historical data, adoption of other work package data for similar ORUs, and engineering judgement. Some life limit estimates were based on specified rather than predicted life.

(5) Evaluation of the approach: reasonable given the immaturity of the design.

(6) Changes in ORU inventory and reliability data from EMTT submittal: some due to design refinements but not enough to significantly affect the results of the study.

(7) Principal maintenance drivers:

(a) Life limits of TV cameras and lights.

(b) Life limit of thermal insulation.

(c) Life limit of airlock seals.

(8) Design changes planned to deal with these items: none currently planned.

(9) Other major reliability design issues: AO degradation of exposed lubricants at articulated joints of remote manipulator.

(10) Comments: Time restraints prevented the SAIC team from making a data acquisition and audit visit to NASDA, so the updated information in the SAIC data base was obtained by correspondence. NASDA did not explicitly separate life limits from random failure rates, but provided enough ancillary information to allow us to identify the design lives of life-limited ORUs. We used the random failure rates of similar ORUs from other Work Packages for these items, since the NASDA failure rates were no longer valid after the life-limit effect was extracted.

5.2.6. Mobile Servicing System (MSS).

(1) Responsible NASA center or international partner agency: Canadian Space Agency.

(2) Scope of supply: Space Station Mobile Remote Servicer (SSMRS), Special Purpose Dextrous Manipulator (SPDM), and MSS Maintenance Depot (MMD).

(3) Principal contractor(s): Spar Aerospace.

(4) Analytical approach: Bottom-up parts count using MIL-HDBK-217E and NPRD-3 generic data plus some subcontractor estimates and accelerated life-test data.

(5) Evaluation of the approach: reasonable given the immaturity of the design.

(6) Changes in ORU inventory and reliability data from EMTT submittal: not significant.

(7) Principal maintenance drivers:

(a) Life limits of thermal blankets.

(b) Life limits of TV cameras and lights.

(c) Life limits of joint drive units.

(d) Life limits of cable harnesses.

(8) Design changes planned to deal with these items: thermal blankets may be integrated with the underlying ORUs so both can be changed out robotically.

(9) Other major reliability design issues: AO degradation of exposed lubricants at articulated joints.

5.2.7. Man-Tended Free Flyer.

(1) Responsible NASA center or international partner agency: European Space Agency.

(2) Scope of supply: Man-Tended Free Flyer.

(3) Principal contractor(s): not available.

(4) Analytical approach: appeared to be engineering-judgement-based allocation of work-package-level reliability targets.

(5) Evaluation of the approach: available backup information was not sufficient to support an evaluation.

(6) Changes in ORU inventory and reliability data from EMTT submittal: not significant.

(7) Principal maintenance drivers: life limits of TV cameras and lights.

(8) Design changes planned to deal with these items: none currently planned.

(9) Other major reliability design issues: possible AO and UV degradation of photovoltaic array "blanket" if similar to Work Package 4's; see paragraph 5.2.4(9)(a).

(10) Comments: Time restraints prevented the SAIC team from making a data acquisition and audit visit to ESA, and the information ESA furnished in response to our data request was not sufficient to validate the pedigree of the updated data. The ESA reliability data in the SAIC data base was extracted from ESA's original EMTT data submittal, with a few changes where failure rates were outside reasonable bounds.

5.2.8. General Evaluation of Work Package and International Partner Reliability Estimates

The observations and conclusions developed in SAIC's audit and review of the WP/IP ORU reliability failure rates were outside reasonable bounds. Estimates can be summarized as follows:

- Except for ESA and NASDA, each of the Work Packages and international partners comprehensively reviewed and updated its original EMTT data submittals before or during SAIC's data acquisition visits.

- Except for ESA, SAIC confirmed that each WP/IP used auditable sources and appropriate, well-documented analytical methodology to develop its estimates.

- ESA did not provide enough back-up information in response to SAIC's request to allow us to validate its methodology. However, in most cases the ESA failure rate estimates are within reasonable bounds as established by the other analyses performed in this study, and are therefore considered credible.

- Conclusion: by and large, the updated WP/IP reliability estimates have been developed from reasonable sources of basic data through the use of appropriate and traceable methodology.

5.3. SAIC External ORU Reliability Data Base.

This section contains the independent, audited SAIC external ORU reliability data base, a summary of the changes which SAIC made in the data submitted to EMTT by the Work Packages and international partners as a result of the data review and audit process, and an inventory of external ORUs by work package and classification.

5.3.1. SAIC Reliability Data Base Structure.

The independent data base SAIC assembled and used for external ORU failure projections is reproduced beginning on page 5-15. The ORU inventory and reliability data in the SAIC data base incorporates all updates and corrections received on or before the closing date of 15 June, 1990 and conforming to the Reliability Data Analysis ground rules given in section 2.4 of this report.

The data base contains the following information supplied by the Work Packages and International Partners (WP/IPs), and extracted directly from the EMTT data base maintained by Ocean Systems Engineering: MTBF, quantity, duty cycle, and ORURELIAB (the EMTT standard ORU type classification, i.e. electronic, electrical, electromechanical, mechanical, structural mechanical, or structural.) Rather than altering this information, which would make our analysis considerably less traceable, SAIC added the following fields:

New MTBFs: Values given to SAIC by the WP/IPs during the data acquisition and review process.

Re-estimated MTBFs: SAIC re-estimated ORU failure rates in those few cases where we considered WP/IP-supplied data to be outside the bounds of realism established by the other analyses in this study, and where the conflict could not be resolved with the WP/IP. We also supplied missing life limits for a few life-limited ORUs. The cases in which SAIC modified WP/IP-supplied data are listed in section 5.3.2.

Life limits: SAIC used WP/IP-supplied life limits for life-limited ORUs without change. (The SAIC reliability data analysis team was not technically qualified to second-guess the ORU designers on this design issue.)

Duty cycle: Similarly, we did not modify the duty cycles provided by the WP/IPs.

5.3.2. SAIC Modifications to Work Package and International Partner Reliability Data.

SAIC changed the data the WP/IPs submitted to the EMTT in the few cases discussed below.

(1) ES.05, External camera: The MTBF was increased to the FTS-supplied value. We considered the failure rate from ESA (about one failure per year) unrealistically high.

(2) ES.06, External lights: ESA's unrealistically low MTBF was increased to the FTS value and the FTS life limit added.

(3) FT.03 and FT.14, Robot manipulator arm and stabilizer arm: Each ORU type contains several actuators whose reliabilities appear to have been underestimated by the work package. We re-analyzed these using data from NPRD-3, which increased the ORU MTBF by a factor of 2.

(4) Various life-limited Japan Experiment Module ORUs (with index numbers in the series NAxxx): NASDA did not explicitly separate random failure rates from life limits for life-limited ORUs in either its EMTT submittal or its update to SAIC, and NASDA's MTBFs for these ORUs were clearly determined by the life limits. Fortunately, the information on the sources of the data in the updated data package included design lives where appropriate. For the life- limited JEM ORUs, the life limits were extracted from the NASDA comments, and random-failure MTBFs of similar ORUs were used from other WP/IPs. (We used the NASDA MTBFs of non-life-limited ORUs without change.)

(5) W2/7.36, Various tools: Simple tool MTBFs were overestimated for the duty cycles given.

5.3.3. Current ORU Inventory

One of the goals of this study was to obtain an updated count of ORUs that would require EVA to repair or replace. For the purposes of this study, an ORU is anything that may be changed-out on-orbit, and is located externally to the pressurized volumes of the space station. The "bean count", or inventory tabulated by Work Package/International Partner and ORU type, is shown in Figure 5.1. As laid out by the ground rules of this study, the count is based on the January, 1990 SSF design. It has changed significantly since the original EMTT data collection effort, and can be expected to change noticeably before construc-tion of the SSF. Throughout this study, the total ORU count (8158), the total number of non-structural (not classified as structural or structural-mechanical) ORUs (3553), and different ORUs (511) are frequently used.

5.3.4. Data Base

The complete audited SAIC external ORU reliability data base is reproduced as Table 5-1 on pages 5-14 though 5-24.

"Bean Count" of ORUs By Type and Work Package

Work Package	Electronic	Electrical	Electro-Mech	Mechanical	Struct-Mech	Structural	ALL
CSA	56	15	32	3	34	73	213
ESA	—	14	5	4	25	—	48
NASDA	17	5	17	38	46	3	126
WP01	—	20	63	16	276	14	389
WP02	180	987	688	947	3538	551	6891
WP03	26	19	15	10	6	3	79
WP04	48	252	48	28	—	36	412
ALL	327	1312	868	1046	3925	680	8158

Figure 5.1

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Table 5-1

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ANALYSIS DATA BASE

ORU		FP QUANTITY	WEM QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORURELIAB	SAIC Approx. Total	NASA/LEWIS MTTF Total
W1.10	M/D Shield	246	246	1000041.6	1000041.6	0.0		10.00	0.00	1.000000	Structmech	408	771
W2.30	Payload Interface (APAS)	20	20	14062.0	14062.0	0.0			0.00	1.000000	Electromech	354	354
W4.02	Battery Subassembly	48	48	52998.0	174061.2	0.0		6.50	0.00	1.000000	Electrical	264	260
W2/7.14.4.E	Radiator Panel	88	88	100000.0	257200.0	0.0	8.00	10.00	12.00	0.000000	Structural	229	269
W2/7.13.8.???	MDM (C-10)	0	48	0.0	25792.0	0.0			0.00	0.370000	Electronic	212	212
E5.06	External Light	12	12	2500.0		20000000.0		2.00	0.00	1.000000	Electrical	176	180
W2/2.12.7.???	EVA Floodlight	0	30	0.0	22000.0	0.0	4.00	9.00	14.00	0.000000	Electrical	152	134
W2/7.13.8.???	MDM (C-4)	0	51	0.0	41079.0	0.0			0.00	0.370000	Electronic	141	141
W2/7.16.4.A	External TV Camera Assembly	0	0	7242.0	12379.0	0.0	1.50	3.75	6.00	0.300000	Electromech	135	109
W4.27	RPC Type 1 (10 A)-/Tolerab.	75	75	156278.4	430203.6	0.0		20.00	0.00	1.000000	Electrical	121	137
MA.34	MLI of EF	40	40	0.0	87600.0	1000000.0		10.00	0.00	1.000000	Structmech	111	125
W4.08	DDCU (12.5 Kw)	32	32	74905.6	150934.0	0.0		15.00	0.00	1.000000	Electrical	108	96
W4.01	DCDU	24	24	86023.2	99864.0	0.0		15.00	0.00	1.000000	Electronic	99	86
MA.10	TV Camera & Light	3	3	8000.0	8000.0	0.0			0.00	1.000000	Electromech	99	99
W2/7.13.8.???	MDM (C-16)	0	16	0.0	19970.0	0.0			0.00	0.370000	Electronic	91	91
W2/4.21.6.A	Resistojet Module	4	4	20000.0	2100.0	0.0	13.00	20.00	26.00	0.867000	Electromech	88	80
W1.20	Window/Trap	12	12	40296.0	40033.2	0.0			0.00	1.000000	Structural	79	79
W2/7.14.5.A	Pump Assembly	0	0	26025.0	30830.0	0.0	8.00	10.00	12.00	1.000000	Electromech	74	60
E5.05	External Camera	4	4	7242.0	7242.0	200000.0		2.00	0.00	1.000000	Electromech	62	62
W4.33	RPC Type 4-/(130 A)-/Tolerab.	37	37	156270.4	431079.6	0.0		20.00	0.00	1.000000	Electrical	60	60
SP.07	CCTV Camera, Light & PTU Assy	2	2	3572.0	3572.0	0.0			0.00	0.330000	Electromech	50	50
SP.06	CCTV Camera, Light & PTU Assy	2	2	3572.0	3572.0	0.0			0.00	0.330000	Electromech	50	50
SP.56	MBS Thermal Blanket	0	0	36500.0	36500.0	0.0			0.00	1.000000	Structmech	50	50
SP.04	MMD Thermal Blankets	0	0	36500.0	36500.0	0.0			0.00	1.000000	Structmech	50	50
W4.25	PVCU	0	0	85760.4	49756.0	0.0		15.00	0.00	1.000000	Electronic	54	65
MA.26	CAP (Relief/Vent Dump Valve)	10	10	50000.0	50000.0	0.0			0.00	1.000000	Mechanical	53	53
SP.08	CCTV Cameras and Lights	2	2	3125.0	3125.0	0.0			0.00	0.210000	Electromech	49	49
W4.31	RPC Type 3 (50 A)-/Tolerab.	29	29	156190.0	431167.2	0.0		20.00	0.00	1.000000	Electrical	47	53
W4.26	Pump	0	0	62896.0	62203.6	0.0		15.00	0.00	1.000000	Electromech	46	38
W2/7.14.5.6.A	Pressure Regulator (N2)	9	4	34370.0	33000.0	0.0	8.00	10.00	12.00	1.000000	Mechanical	42	34
SP.64	Upper Body CCTV (Stereo)	1	1	2500.0	2500.0	0.0			0.00	0.330000	Electromech	42	42
W2/7.14.5.B	Pressure Regulator Ammonia	0	4	34370.0	33060.0	0.0	8.00	10.00	12.00	1.000000	Mechanical	41	34
AP.2	4X ORU	0	4	0.0	402960.0	0.0		3.00	0.00	1.000000	Electronic	41	41
W2/2.12.7.D	EVA Luminare	32	0	12000.0	22000.0	0.0	4.00	9.00	14.00	0.000000	Electrical	40	36
W2/7.16.4.B	External Video Switch	2	4	13592.0	15009.0	0.0			0.00	0.300000	Electronic	39	39
SP.11	Dexterous Arm	2	2	5432.0	5432.0	0.0			0.00	0.330000	Electromech	38	38
W2/7.30.10.???	Slidewire	0	13	0.0	72070.0	0.0	8.00	10.00	12.00	0.000400	Structmech	37	41
MA.35	EEU (Equip. Exchange Unit)	13	13	0.0	87600.0	1000000.0		10.00	0.00	1.000000	Mechanical	36	41
W2/2.12.7.???	Fixed Ext Lights	0	0	0.0	22000.0	0.0		9.00	0.00	0.000000	Electrical	34	32
SP.09	CCTV Cameras and Lights	2	2	6250.0	6250.0	0.0			0.00	0.330000	Electromech	33	33
SP.04	Arm CCTV (With Lights)	2	2	6250.0	6250.0	0.0			0.00	0.330000	Electromech	33	33
W1.17	Trap Window Shutters	12	12	100039.2	100039.2	0.0			0.00	1.000000	Electromech	32	32
W2/7.14.5.D	Recirculating Control Valve	0	4	900900.0	66740.0	0.0	4.00	5.00	6.00	0.500000	Electromech	31	29
W1.15	Shut-Off Valves	30	28	246856.0	246856.0	0.0			0.00	1.000000	Electromech	30	30
W2/2.20.3.F.???	N2 Press/vent Safety Assy	0	2	0.0	17900.0	0.0			0.00	1.000000	Mechanical	29	29
W2/2.20.3.F	N2 Pressure Sensor Assembly	2	2	600000.0	17900.0	0.0			0.00	1.000000	Electromech	29	29
SP.35	Main Body CCTV, Light & PTU	1	1	3572.0	3572.0	0.0			0.00	0.330000	Electromech	29	29
W2/2.22.4.A.A	Interconnect Lines	227	204	1000000.0	2504000.0	0.0			0.00	1.000000	Mechanical	29	29
W4.07	DCSU	0	0	125092.0	125092.0	0.0		15.00	0.00	1.000000	Electronic	29	26
SP.32	Boom Thermal Blankets	4	4	36500.0	36500.0	0.0			0.00	1.000000	Structmech	29	29
SP.72	Roll/Yaw Jnt Noing Ther Blnkt	4	4	36500.0	36500.0	0.0			0.00	1.000000	Structmech	29	29
W4.04	Beta Gimbal Assy (IN-SITU)	0	8	131400.0	131400.0	0.0		15.00	0.00	1.000000	Structural	28	19
SP.30	PMDS/DMS Electronics Unit	2	2	11532.0	11532.0	0.0			0.00	0.550000	Electronic	27	27
W2/7.16.3.A.A	SSS Omni Antenna	6	4	700000.0	35313.0	0.0			0.00	0.090000	Electrical	27	27
W2/2.19.3.A.B	Drive Assembly	4	0	22646.0	39291.0	0.0			0.00	1.000000	Electromech	27	27
W2/2.19.4.A.B	Drive Assembly	4	4	22646.0	39291.0	0.0			0.00	1.000000	Electromech	27	27

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Table 5-1 (continued)

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	ORU	FP QUANTITY	WEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORURELIAB	SAIC Approx. Total	NASA/LEWIS MTTF Total
SP.10	IVA IFS Hand Controller	2	2	6410.0	6410.0	0.0			0.00	0.250000	Electromech	27	27
U4.24	Fluid Junction Box	0	0	01906.0	01906.0	0.0			0.00	1.000000	Mechanical	26	26
U2/7.14.5.???	Cold Plate Assy	0	24	0.0	240760.0	0.0			0.00	1.000000	Mechanical	25	25
SP.20	Latching End Effector (LEE)	2	2	20044.0	20044.0	0.0			0.00	1.000000	Electromech	25	25
SP.30	Payload/ORU Accommodation Unit	2	2	20044.0	20044.0	0.0			0.00	1.000000	Electromech	25	25
U4.21	PV Blanket & Box (L & R)	16	16	122013.2	6370331.0	0.0		15.00	0.00	1.000000	Electromech	25	22
U2/2.20.5.A.F	HHC Dryer Assembly	2	2	500000.0	39300.0	0.0	3.00	5.00	10.00	1.000000	Electrical	24	20
U2/2.20.5.B.E	HHC Dryer Assembly	2	2	200000.0	39300.0	0.0	3.00	5.00	10.00	1.000000	Electrical	24	20
U2/7.10.3.B.A	Heat Exchanger Units	10	32	72516.0	345070.0	0.0			0.00	1.000000	Mechanical	24	24
U2/5.36.6.???	EV charged Part Dir Spect	0	1	0.0	19530.0	0.0		3.00	0.00	1.000000	Electronic	23	10
U2/2.12.7.???	FTS Luminaire	0	16	0.0	22000.0	0.0	36.00	35.00	34.00	0.021000	Electrical	23	20
FT.00	Contamination Sensor	4	4	1120000.0	10000000.0	0.0		5.00	0.00	1.000000	Electronic	22	24
FT.04	Battery (20Ah) (Thermal Cont)	3	3	33210.7	1000000.0	0.0		4.00	0.00	1.000000	Electrical	22	23
SP.71	Pitch Joint Being Ther Blanket	3	3	36500.0	36500.0	0.0			0.00	1.000000	Structmech	22	22
U2/7.14.5.???	Pressure Reducing Station	0	2	0.0	32100.0	0.0	0.00	10.00	12.00	1.000000	Mechanical	21	10
U2/2.20.3.???	Outlet Dcr/Vent Assy	0	2	0.0	24700.0	0.0			0.00	1.000000	Electromech	21	21
U2/2.12.7.B	Video Camera Luminaire	11	0	2500.0	22000.0	0.0	9.00	10.00	27.00	0.042000	Electrical	21	21
SP.21	Joint Drive Unit	7	7	07260.0	07260.0	0.0			0.00	1.000000	Electronic	21	21
AP.3	-X ORU	0	4	0.0	49932.0	0.0			0.00	1.000000	Electronic	21	21
U1.14	PRTC Valves	6	3	40296.0	40033.2	0.0			0.00	1.000000	Electromech	20	20
U2/7.36.10.A	EVA Portable Light Assy	2	4	2500.0	41171.0	0.0	0.00		12.00	0.009000	Electrical	20	5
U2/5.36.5.B.B	Port. Contamination Detector	2	2	25000.0	4054.0	0.0			0.00	0.009000	Electronic	20	20
U2/2.19.4.A.6	Fluid Coupler	2	2	500000.0	36560.0	0.0	0.00	10.00	12.00	1.000000	Mechanical	19	16
U4.12	Beta Gimbal Drive Motor Cont	0	0	105820.0	292759.2	0.0		15.00	0.00	1.000000	Electronic	19	20
U2/7.17.4.A	Control Moment Gyro Assy (CMG)	6	6	672000.0	334232.0	0.0	999.00	10.00	0.00	0.750000	Electromech	19	20
U2/3.12C?	Upper Base	1	1	500000.0	14490.0	0.0			0.00	1.000000	Structural	18	18
U2/2.22.4.F.A	Fluid Control Cable Assembly·	20	135	100000.0	1960000.0	0.0			0.00	1.000000	Electrical	18	18
U2/5.36.9.A	Handrails	21	21	1000000.0	31725.0	0.0			0.00	0.000100	Structural	18	18
U2/2.20.5.A.D	HHC Compressor Assembly	2	2	100000.0	23500.0	0.0	5.00	10.00	12.00	0.500000	Electromech	17	14
U2/2.20.5.B.D	HHC Compressor Assembly	2	2	50000.0	23500.0	0.0	5.00	10.00	12.00	0.500000	Electromech	17	14
U4.10	MBSU - ITA	4	4	64290.4	94695.6	0.0		15.00	0.00	1.000000	Electrical	17	15
U4.37	SSU	0	0	04096.0	440336.0	0.0		15.00	0.00	1.000000	Electrical	17	10
U2/3.12C?	Upper Base Latch Assembly	4	4	500000.0	64316.0	0.0			0.00	1.000000	Electromech	16	16
U2/9.40.3.C.B	Umbilical Service Sec Elec	0	120	0.0	1960000.0	0.0			0.00	1.000000	Electrical	16	16
FT.35	Camera Lamps	0	0	17520.0	20000000.0	0.0		11.11	0.00	0.100000	Electrical	16	22
EA.00	HDPS cylindrical sections	16	16	262000.0	262000.0	0.0			0.00	1.000000	Structmech	16	16
U2/5.35.4.A.B	Depress Disp. Cont. Pal (EXT)	1	6	43000.0	100100.0	0.0	0.00	10.00	12.00	0.000100	Electronic	16	10
U2/2.20.3.A	H2 DC Heater Assembly	2	2	50000.0	19100.0	0.0			0.00	0.500000	Electrical	15	15
SP.20	Joint Drive Unit	5	5	07260.0	07260.0	0.0			0.00	1.000000	Electronic	15	15
U2/7.14.5.???	Relief Valve	0	28	0.0	494560.0	0.0			0.00	1.000000	Mechanical	15	15
U2/7.36.10.???	O2 Compression and Storage	0	2	0.0	10625.0	0.0	0.00	10.00	12.00	0.011000	Electromech	15	12
SP.23	Joint Electronics Unit (JEU)	14	14	72729.0	72729.0	0.0			0.00	0.210000	Electronic	15	15
U4.29	RPC Type 2 (25 A)-/Telecmb.	9	9	156270.4	430904.4	0.0		20.00	0.00	1.000000	Electrical	14	16
U2/7.16.4.???	Video Interface Converter	0	4	0.0	40000.0	0.0			0.00	0.500000	Electronic	14	10
SP.73	Roll/Yaw Jnt Beng Ther Blanket	2	2	36500.0	36500.0	0.0			0.00	1.000000	Structmech	14	14
SP.74	PJE (B & U) Thermal Blanket	2	2	36500.0	36500.0	0.0			0.00	1.000000	Structmech	14	14
U1.02	Interface Assembly	0	0	140044.0	147860.0	0.0			0.00	1.000000	Mechanical	14	14
FT.10	Double V-block Tool	2	2	465000.0	175200.0	0.0		5.00	0.00	1.000000	Mechanical	14	10
U4.15	IEA (IN-SITU)	4	4	131400.0	131400.0	0.0		15.00	0.00	1.000000	Structural	14	9
U2/7.14.5.C	Accumulator	4	4	21639.0	269400.0	0.0	0.00	10.00	12.00	1.000000	Mechanical	14	14
U2/7.17.4.A	Inertial Sensor Assembly	3	3	94000.0	53655.0	0.0	999.00	10.00	0.00	0.250000	Electromech	13	12
HA.16	Seal-Airlock Pressure Equal.	1	1	20000.0	20000.0	0.0			0.00	1.000000	Mechanical	13	13
HA.15	Seal Airlock Outer Hatch	1	1	20000.0	90000.0	0.0			0.00	1.000000	Structmech	13	13
U1.19	Windows/Round	5	2	40296.0	40033.2	0.0			0.00	1.000000	Structural	13	13
U4.09	DDCU-IEA	4	4	74903.6	150934.0	0.0		15.00	0.00	1.000000	Electrical	13	12
U2/2.22.4.C.A	Flex Hose	30	77	50000.0	1575000.0	0.0			0.00	1.000000	Mechanical	13	13

Table 5-1 (continued)

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ANALYSIS DATA BASE

	ORU	FP QUANTITY	NEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORUREL1AB	SAIC Approx. Total	NASA/LEWIS MTTF Total
W2/3.10.4.???	Trans. Emer Stor Sys (TESSO)	0	4	0.0	40520.0	0.0	0.00	10.00	12.00	0.003000	Electrical	13	13
SP.24	LEE - Base	1	1	20044.0	20044.0	0.0			0.00	1.000000	Mechanical	13	13
SP.07	LEE	1	1	20044.0	20044.0	0.0			0.00	1.000000	Electromech	13	13
MA.14	SPC Signal Processing Controll	4	4	87600.0	87600.0	0.0			0.00	1.000000	Electronic	12	12
MA.33	VSW Video Switcher	4	4	87600.0	87600.0	0.0			0.00	1.000000	Electronic	12	12
MA.02	ESC EF System Controller	4	4	87600.0	87600.0	0.0			0.00	1.000000	Electronic	12	12
MA.13	PSU EF Power Switching Unit	4	4	87600.0	87600.0	0.0			0.00	1.000000	Electrical	12	12
MA.08	EE for EF	2	2	0.0	43000.0	0.0			0.00	1.000000	Mechanical	12	12
W2/5.36.9.D	Portable Foot Restraints PFRs	2	4	200320.0	79891.0	0.0	0.00	10.00	12.00	0.005000	Structmech	12	13
W2/2.20.5.A.???	NMG Inlet Vent/Safe Assy	0	1	0.0	22600.0	0.0			0.00	1.000000	Mechanical	12	12
W2/2.20.5.B.???	NMG Inlet Vent/Safe Assy	0	1	0.0	22600.0	0.0			0.00	1.000000	Mechanical	12	12
W2/2.21.7.6.C	Umbilical Mechanism	0	24	300000.0	300000.0	0.0			0.00	0.500000	Electromech	12	12
W2/2.22.3.C.G	Pallet Power Cable Assy. -015	44	88	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	12	12
W2/7.36.10.???	Ford Portable Foot Restraint	0	4	0.0	110011.0	0.0	0.00	10.00	12.00	0.006000	Electromech	11	13
W2/5.36.9.C	Safety Tether Reels	2	4	100000.0	110339.0	0.0	0.00	10.00	12.00	0.005000	Structmech	11	13
W2/2.22.3.C.A	Pallet Power Cable Assy. -003	41	82	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	11	11
FT.14	Manipulator	2	2	24000.0	59179.0	24027.0		10.00	0.00	0.100000	Electromech	11	9
W2/2.20.5.B.B	NMG Vent/Safety Assembly	1	1	500000.0	24500.0	0.0			0.00	1.000000	Electromech	11	11
W2/2.20.5.A.B	NMG Vent/Saftey Assembly	1	1	200000.0	24500.0	0.0			0.00	1.000000	Electromech	11	11
W2/9.40.3.C.A	Umbilical Service Set Fluid	1	66	350000.0	1575000.0	0.0			0.00	1.000000	Electromech	11	11
W2/7.36.10.???	OCSS Pwr Supply	0	2	0.0	1506024.0	0.0	0.00		12.00	1.000000	Electrical	11	3
W2/7.16.7.C.A	Ku-Band TDRSS T-R (SGT-R)	4	4	42194.0	35605.0	0.0			0.00	0.205000	Electronic	11	11
W2/2.20.5.A.???	NMG Tank Press Ind Assy	0	1	0.0	25000.0	0.0			0.00	1.000000	Mechanical	11	11
W2/2.20.5.B.???	NMG Tank Press Ind Assy	0	1	0.0	25000.0	0.0			0.00	1.000000	Mechanical	11	11
W1.23	Electrical Junction Box	4	4	99064.0	100039.2	0.0			0.00	1.000000	Electrical	11	11
SP.22	Joint Electronics Unit (JEU)	10	10	72729.0	72729.0	0.0			0.00	0.210000	Electronic	10	10
W2/7.14.4.A	Condenser/Subcooler Module	20	22	72516.0	363060.0	0.0			0.00	1.000000	Mechanical	10	10
W2/2.22.4.A.E	Umbilical Flex Hose	30	61	45000.0	1565000.0	0.0			0.00	1.000000	Mechanical	10	10
MA.31	Airlock Table	1	1	0.0	26200.0	0.0			0.00	1.000000	Structmech	10	10
ES.10	Viewport Ext Drive Mech	1	1	26200.0	26209.0	0.0			0.00	1.000000	Electromech	10	10
W2/2.12.4.B.E.C	Deployable Util Tray Covers	742	1400	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	10	10
W2/9.40.3.C.C	Umb. Svc. Set Attch Panel	0	0	0.0	220000.0	0.0			0.00	1.000000	Electrical	10	10
SP.01	MMD PMDS/DMS Electronic Unit	2	2	16712.0	16712.0	0.0			0.00	0.210000	Electronic	9	9
W2/7.17.3.A	Star Tracker	3	3	250000.0	413240.0	0.0	999.00	10.00	0.00	0.670000	Electromech	9	10
MA.22	Thermal Insu. A/L Outer Hatch	1	1	30000.0	30000.0	0.0			0.00	1.000000	Structmech	9	9
ES.02	Airlock Outer Hatch Seal	1	1	30000.0	30000.0	0.0			0.00	1.000000	Mechanical	9	9
SP.40	SPDM Main Cont Computer (MCC)	2	2	17826.0	17826.0	0.0			0.00	0.210000	Electronic	9	9
SP.05	Arm Control Unit (ACU)	2	2	17826.0	17826.0	0.0			0.00	0.210000	Electronic	9	9
W2/2.20.3.???	N2 Purge Assy	0	1	0.0	30900.0	0.0			0.00	1.000000	Mechanical	9	9
W2/2.20.5.B.???	NMG Accumulator Press Ind	0	1	0.0	31300.0	0.0			0.00	1.000000	Mechanical	8	8
W2/2.20.5.A.???	NMG Accum Press Ind	0	1	0.0	31300.0	0.0			0.00	1.000000	Mechanical	8	8
MA.27	Window Pane	3	3	87600.0	87600.0	1000000.0		10.00	0.00	1.000000	Structural	8	9
W2/2.22.4.B.E	Umbilical Flex Hose	24	49	45000.0	1575000.0	0.0			0.00	1.000000	Mechanical	8	8
W2/7.14.5.E.G	Isolation Valve	12	390	900900.0	1272260.0	0.0			0.00	0.001000	Electromech	8	8
W2/7.13.???	Ring Concentrator (RC)	10	4	81000.0	129439.0	0.0			0.00	1.000000	Electronic	8	8
W2/7.14.3.???	Pressure Dome Assy	0	88	0.0	2057140.0	0.0			0.00	1.000000	Mechanical	8	8
FT.09	Crew Warning Device	4	4	4960000.0	20000000.0	0.0		11.10	0.00	0.100000	Electronic	8	11
ES.11	MPDS end cones	0	0	262000.0	262000.0	0.0			0.00	1.000000	Structmech	8	8
W2/2.19.6.A.A	Berthing Latch Assembly	30	30	500000.0	100000.0	0.0			0.00	0.000100	Electromech	8	8
W2/7.14.5.I.A	Supply / Dump Tank Assy	1	0	125000.0	269400.0	0.0			0.00	1.000000	Mechanical	8	8
W2/2.22.4.B.A	Flex Hose	22	46	5035000.0	1575000.0	0.0			0.00	1.000000	Mechanical	8	8
W2/2.22.3.C.C	Pallet Power Cable Assy. -007	28	56	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	8	8
W2/7.36.10.???	Aux Service Power Tools	0	2	0.0	23020.0	100000000.0	0.00		12.00	0.000000	Mechanical	8	8
SP.36	OMNI Antenna	0	0	83333.0	83333.0	0.0			0.00	0.210000	Electrical	7	7
SP.79	SPDM LBS Thermal Blanket	1	1	36500.0	36500.0	0.0			0.00	1.000000	Structmech	7	7
SP.77	SPDM UBS Thermal Blanket	1	1	36500.0		0.0			0.00	1.000000	Structmech	7	7

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	ORU	FP QUANTITY	NEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORURELIAB	SAIC Approx. Total	NASA/LEWIS MTTF Total
SP.75	DJH (Hock) Thermal Blanket	1	1	36500.0	36500.0	0.0			0.00	1.000000	Structmech	7	7
W1.03	Interface Manifold	4	4	140044.0	147060.0	0.0			0.00	1.000000	Mechanical	7	7
SS.04	DC/DC Converter Units (DDCU)	2	2	74985.0	74985.0	0.0			0.00	1.000000	Electrical	7	7
W2/5.36.6.B	Portable Work Platform Stowage	2	2	1000000.0	31476.0	0.0	0.00	10.00	12.00	0.001000	Structmech	7	7
W1.22	Power Cables	16	16	620442.4	620442.4	0.0			0.00	1.000000	Electrical	7	7
W2/7.36.10.???	Tether Loops	0	370	0.0	1474926.0	0.0			0.00	0.000100	Structmech	7	7
SP.02	Antenna Mounted Elec (AME)	4	4	45030.0	45030.0	0.0			0.00	0.210000	Electrical	7	7
W2/7.17.0.?	CMG Electronics Assy	12	12	94000.0	210922.0	0.0			0.00	0.375000	Electronic	7	7
W2/3.3.3.???	APA LINEAR DEPLOY ACTUATOR	0	12	0.0	61656.0	0.0			0.00	0.003000	Electromech	6	6
W2/3.3.3.???	APA ROTARY ACTUATOR	0	12	0.0	61656.0	0.0			0.00	0.003000	Electromech	6	6
W2/5.36.9.J	Clothesline Assembly	2	2	100000.0	49719.0	0.0	0.00	10.00	12.00	0.004000	Structmech	6	7
W2/7.36.10.???	Manipulator Foot Restraint	0	2	0.0	43170.0	0.0	0.00	10.00	12.00	0.002000	Structmech	6	7
W2/2.22.3.B.0	Interface Pow.Cable Assy. -015	24	48	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	6	6
W1.14	Vent & Relief Isolation Valve	10	8	247032.0	333756.0	0.0			0.00	1.000000	Electromech	6	6
W2/2.20.3.F.???	N2 to TMRS Assy	0	1	0.0	41000.0	0.0			0.00	1.000000	Mechanical	6	6
W2/2.20.3.???	N2 to TMCS Assy	0	1	0.0	41000.0	0.0			0.00	1.000000	Mechanical	6	6
W2/5.36.9.B	CETA Manual Cart	1	1	200320.0	12192.0	0.0	0.00	10.00	12.00	0.000000	Mechanical	6	5
W2/5.36.9.F	PFR Socket	10	470	200320.0	2000000.0	0.0			0.00	0.000020	Structmech	6	6
W2/2.12.4.B.E.B	Deployable Util Tray Carrier	915	915	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	6	6
MA.03	EMU EF Heat Exchanger	2	2	87600.0	87600.0	0.0			0.00	1.000000	Mechanical	6	6
W2/2.22.3.C.B	Pallet Power Cable Assy. -017	22	44	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	6	6
MA.11	MLI	1	1	43000.0	43000.0	1000000.0		5.00	0.00	1.000000	Structmech	6	6
W4.10	Deployable Mast & Canister	8	8	141290.0	367744.0	0.0			0.00	1.000000	Electromech	6	6
W2/7.16.5.A	SSS Transmitter-Rec Type 3	6	4	19719.0	35605.0	0.0			0.00	0.010000	Electronic	6	6
W2/7.36.10.???	GCSS Controller	0	2	0.0	933707.0	0.0	0.00	10.00	12.00	1.000000	Electronic	6	6
FT.10	Rotary Tool Holster	2	2	507000.0	1000000.0	0.0		3.00	0.00	1.000000	Mechanical	6	6
MA.06	FAU Freon Accumulator Unit	2	2	87600.0	87600.0	1000000.0		3.00	0.00	1.000000	Mechanical	6	6
FT.31	Module Servicing Tool (MST)	1	1	39053.0	100000000.0	0.0		5.00	0.00	1.000000	Electromech	6	6
FT.33	Node Attachment Tool (NAT)	1	1	154904.0	100000000.0	0.0		5.00	0.00	1.000000	Mechanical	6	6
FT.32	Radiator Panel Tool (RPT)	1	1	154904.0	100000000.0	0.0		5.00	0.00	1.000000	Mechanical	6	6
W2/2.20.3.???	Q.D. (Gas)	0	74	0.0	3636000.0	0.0			0.00	1.000000	Mechanical	5	5
W2/2.20.3.???	Quick Disconnects	0	74	0.0	3636000.0	0.0			0.00	1.000000	Mechanical	5	5
MA.07	FPP Freon Pump Package	2	2	87600.0	87600.0	1000000.0		10.00	0.00	0.500000	Electromech	5	6
MA.25	Emergency CO2 Exhaust Nozzle	1	1	50000.0	50000.0	0.0			0.00	1.000000	Mechanical	5	5
MA.30	Airlock Outer Hatch Mechanism	1	1	0.0	50000.0	0.0			0.00	1.000000	Mechanical	5	5
W2/2.19.4.A.A	Bearing Assembly	2	2	500000.0	100000.0	0.0			0.00	1.000000	Mechanical	5	5
W2/2.19.6.A.F	Harness 1553 Bus Log Carr Bert	26	10	500000.0	500000.0	0.0			0.00	1.000000	Electrical	5	5
W1.10	Round Window Shutter	5	2	100039.2	100039.2	0.0			0.00	1.000000	Electromech	5	5
W2/2.12.7.???	AMP Luminaire	0	4	0.0	22000.0	0.0			0.00	0.011000	Electrical	5	5
W1.06	Valve with Heater	2	2	100139.2	100139.2	0.0			0.00	1.000000	Electromech	5	5
W2/7.16.7.B.A	TDRSS Parabolic Ant (SGANT)	2	2	70000.0	102733.0	0.0	11.00	16.00	21.00	0.570000	Electromech	5	6
W2/2.22.4.C.B	Fittings	194	194	10000000.0	10000000.0	0.0			0.00	1.000000	Structmech	5	5
FT.15	Parallel Jaw Holster	2	2	507000.0	10000000.0	0.0		10.00	0.00	1.000000	Structmech	5	6
W2/5.36.5.B.C	Contamination Removal Unit.	2	2	100000.0	1615509.0	0.0	0.00	10.00	12.00	0.001000	Electrical	5	6
FT.11	EECM Holster	2	2	507000.0	50000000.0	0.0		10.00	0.00	1.000000	Structmech	5	6
W2/7.36.10.???	Misc. EVA Support Equip	0	2	0.0	2020.0	100000000.0	0.00	10.00	12.00	0.006000	Structmech	5	6
W2/7.36.10.???	EVA Tool Storage Device	0	2	0.0	370096.0	100000000.0	0.00	10.00	12.00	0.002000	Structmech	5	6
W1.12	MLI (Fwd Trunions & Keel Pins)	18	18	1000041.6	1000041.6	0.0			0.00	1.000000	Structmech	5	5
FT.06	CPA Camera	2	2	200000.0	327069.0	0.0		11.10	0.00	0.100000	Electromech	4	6
W4.16	TCA (R/B)	4	4	525600.0	230096.0	0.0			0.00	1.000000	Structural	4	4
W2/9.19.9	Slide Mechanism	3	3	20000.0	20000.0	0.0			0.00	0.010000	Electromech	4	4
W2/2.21.7.6.F	Harness 1553 Bus. Prop Berth	16	8	500000.0	500000.0	0.0			0.00	1.000000	Electrical	4	4
W2/2.21.7.6.B	Propulsion Wire Harness	8	8	500000.0	500000.0	0.0			0.00	1.000000	Electrical	4	4
W2/2.20.3.???	SC H2 Crossover	0	1	0.0	62700.0	0.0			0.00	1.000000	Mechanical	4	4
SP.06	Video Bus Interface Unit VBIU	4	4	72729.0	72729.0	0.0			0.00	0.210000	Electronic	4	4
W4.11	Beta Gimbal Drive Motor Assy	8	8	66400.0	500255.2	0.0			0.00	1.000000	Electromech	4	4

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ORU		FP QUANTITY	NEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORUREL1AB	SAIC Approx. Total	NASA/LEWIS MTTF Total
FT.25	Workstation SDP	2	2	790000.0	34247.0	0.0			0.00	0.180000	Electronic	4	4
W4.22	PV Cable Set	4	4	103360.0	262000.0	0.0			0.00	1.000000	Electrical	4	4
FT.03	Stabilizer ASPS	1	1	24759.0	75815.0	28404.0		15.00	0.00	0.100000	Electromech	4	3
W2/5.19.3.A.E	Seal Set	1	1	100000.0	800000.0	0.0	5.00	7.50	10.00	1.000000	Mechanical	4	4
W2/2.22.3.A.I	Port C & T Cable Assy. - Power	1	20	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	4	4
W2/2.22.3.A.J	Stbd. C & T Cable Assy.- Power	1	20	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	4	4
W1.01	Interface Manifold	2	2	148044.0	147068.0	0.0			0.00	1.000000	Mechanical	4	4
W4.35	Radiator Subassembly	4	4	67090.0	297040.0	0.0			0.00	1.000000	Mechanical	4	4
E5.07	Heat Exchangers	2	2	1500000.0	150000.0	0.0			0.00	1.000000	Mechanical	4	4
W2/2.19.6.???	Umbilical Mech Elec I/F	0	4	0.0	300000.0	0.0			0.00	1.000000	Electromech	4	4
W2/2.19.6.A.C	Umbilical Mechanism	10	4	300000.0	300000.0	0.0			0.00	1.000000	Electromech	4	4
W2/3.10.4.???	Remote Pwr Dist Elect	0	2	0.0	151000.0	0.0			0.00	1.000000	Electrical	3	3
W2/7.36.10.???	Light/CCTV Position Arms	0	4	0.0	50060.0	0.0			0.00	0.007000	Electromech	3	3
W2/2.22.3.B.B	Interface Pow.Cable Assy. -017	12	24	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	3	3
W2/3.12.6.A	Drive Hinge Assembly	1	1	125000.0	19306.0	0.0			0.00	0.013000	Electromech	3	3
SP.01	AVU	1	1	26709.0	26709.0	0.0			0.00	0.250000	Electronic	3	3
W1.11	MLI (Longerons & AFT Trunions)	12	12	1000041.6	1000041.6	0.0			0.00	1.000000	Structmech	3	3
W1.05	Valve Without Heater	3	3	250014.4	250014.4	0.0			0.00	1.000000	Electromech	3	3
W2/2.20.3.???	H2 800 psi Storage Tank	0	2	0.0	167000.0	0.0			0.00	1.000000	Mechanical	3	3
W2/5.36.6.A	ESET Stowage	2	2	1000000.0	20211.0	0.0			0.00	0.002000	Structmech	3	3
SP.44	RF Unit	1	1	25003.0	25003.0	0.0			0.00	0.210000	Electronic	3	3
FT.26	Antenna Assembly	2	2	500000.0	25000000.0	0.0		15.00	0.00	1.000000	Structural	3	4
MA.20	Seal Cover EN Surface	1	1	87600.0	87600.0	0.0			0.00	1.000000	Mechanical	3	3
W2/2.22.4.E	Fluid Utility Junction Assy	2	2	50000.0	176000.0	0.0			0.00	1.000000	Mechanical	3	3
W2/2.22.3.B.F	Interface Pow.Cable Assy. -013	11	22	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	3	3
MA.17	Main Arm Mechanism	1	1	87600.0	87600.0	0.0		10.00	0.00	0.050000	Electromech	3	3
AP.1	Station Interface Adapter(SIA)	0	4	0.0	367920.0	0.0			0.00	1.000000	Electromech	3	3
FT.20	TR Computer (SDP)	2	2	114000.0	49554.0	0.0			0.00	0.180000	Electronic	3	3
W2/5.19.3.A.G	Latching Mechanism Assembly	1	1	250000.0	96376.0	0.0			0.00	1.000000	Mechanical	3	3
W2/2.22.3.B.D	Interface Pow.Cable Assy. -005	10	20	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	3	3
W2/5.36.9.B	Handholds	10	10	1000000.0	99100.0	0.0			0.00	0.000100	Structural	3	3
SP.60	Tool Changeout Mechanism (TCM)	2	2	79079.0	79079.0	0.0			0.00	0.330000	Electromech	3	3
MA.33	EF-1/EF-2 Berthing Mechanism	1	1	0.0	100000.0	0.0			0.00	1.000000	Mechanical	3	3
MA.36	Berthing Mech. Betw. EF-1 & 2	1	1	0.0	100000.0	0.0			0.00	1.000000	Mechanical	3	3
MA.32	PM/EF-1 Berthing Mechanism	1	1	0.0	100000.0	0.0			0.00	1.000000	Mechanical	3	3
W2/2.12.3.B	Diagonal Strut Assembly	140	100	10000000.0	10000000.0	0.0			0.00	1.000000	Structural	3	3
W2/2.20.3.E	H2 Vent/Safety Assembly	2	2	200000.0	200000.0	0.0			0.00	1.000000	Electromech	3	3
W2/5.36.9.???	CETA Tether Shuttle	0	1	0.0	401929.0	0.0	0.00	10.00	12.00	0.000000	Electromech	3	3
W2/2.12.7.A	Orientation Luminare	7	0	27500.0	83000.0	0.0			0.00	0.003000	Electrical	3	3
W2/2.19.4.A.F	Power/Data Trans Module PDTM	2	2	1000000.0	205090.0	0.0			0.00	1.000000	Electromech	3	3
W2/2.19.3.A.F	Utility Transfer Assy	2	2	1000000.0	205090.0	0.0			0.00	1.000000	Electromech	3	3
W2/2.12.7.B	Free Flyer Luminare	2	2	12000.0	22000.0	0.0			0.00	0.000000	Electrical	3	3
MA.04	End Effector	1	1	87600.0	87600.0	1000000.0		10.00	0.00	0.050000	Mechanical	3	3
MA.29	Bumper (ELM-PS)	1	1	0.0	87600.0	10000000.0		10.00	0.00	1.000000	Structmech	3	3
FT.30	FTS Umbilical Storage Holster	1	1	500000.0	10000000.0	0.0		10.00	0.00	1.000000	Structmech	3	3
FT.34	Radiator Panel Tool Holster	1	1	253035.0	30000000.0	0.0		10.00	0.00	1.000000	Structmech	3	3
MA.17	Small Fine Arm	1	1	14600.0	14600.0	10000000.0		10.00	0.00	0.050000	Mechanical	3	3
W2/7.14.3.???	Gas Trap Assy	0	4	0.0	427900.0	0.0			0.00	1.000000	Mechanical	2	2
W2/2.12.7.L	Docking Target Luminare	2	2	3750.0	22000.0	0.0			0.00	0.003000	Electrical	2	2
SP.19	Joint Control Processor (JCP)	2	2	65359.0	65359.0	0.0			0.00	0.210000	Electronic	2	2
FT.07	Camera Positioning Assy (CPA)	1	1	233000.0	87600.0	0.0		15.00	0.00	0.100000	Electromech	2	2
W2/7.16.10.C	UHF Omni Antenna	4	12	1000000.0	200000.0	0.0			0.00	0.050000	Electrical	2	2
SP.65	Video Distribution Unit	2	2	66684.0	66684.0	0.0			0.00	0.210000	Electronic	2	2
W2/3.3.3.A	APA	0	2	0.0	23507.0	0.0			0.00	0.000200	Electromech	2	2
W2/2.22.3.H	Port Prop. Module Cable Assy.-	1	16	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	2	2
W2/2.22.3.I	Stbd. Prop. Module Cable Assy.	1	16	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	2	2

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ANALYSIS DATA BASE

	ORU	FP QUANTITY	NEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORURELIAB	SAIC Approx. Total	NASA/LEWIS EMTT Total
M2/2.12.3.???	Batten Strut Assembly	0	80	0.0	10000000.0	0.0			0.00	1.000000	Structural	2	2
M1.21	Vent Valve (FMOM)	1	2	249460.0	250010.4	0.0			0.00	1.000000	Mechanical	2	2
SP.07	Video Distribution Unit VDU	2	2	72729.0	72729.0	0.0			0.00	0.210000	Electronic	2	2
M4.36	Beta Gimbal Roll Ring Assembly	8	8	59305.2	1006706.0	0.0			0.00	1.000000	Electromech	2	2
M2/5.19.3.A.F	Actuation Mechanism Assy	1	1	130000.0	130000.0	0.0			0.00	1.000000	Mechanical	2	2
M4.19	PMAD Cable Set	1	2	103368.0	262000.0	0.0			0.00	1.000000	Electrical	2	2
M2/2.19.3.A.I	Locking Mechanism	2	2	99423.0	30643.0	0.0			0.00	0.100000	Electromech	2	2
M2/7.16.3.D	SSS Parabolic Antenna Assembly	4	4	100000.0	103993.0	0.0			0.00	0.010000	Electrical	2	2
M2/2.22.3.C.F	Pallet Power Cable Assy. -013	7	14	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	2	2
MA.09	ITV/LZ TV Camera Assembly	2	2	7971.6	80000.0	0.0			0.00	0.200000	Electromech	2	2
M2/5.36.6.C	EV Umbilical Stowage System	1	2	1000000.0	34330.0	0.0			0.00	0.001000	Structmech	2	2
M2/7.36.10.???	Mini Workstation	0	4	0.0	80320.0	0.0			0.00	0.003000	Structmech	2	2
M2/7.16.7.C.D	Ku-Band TDRSS Ant Cntrl (DBAC)	4	4	60000.0	231002.0	0.0			0.00	0.203000	Electronic	2	2
M2/2.22.3.D.D	Interface Pow.Cable Assy. -009	6	12	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	2	2
M2/2.12.3.C	Truss Node Assembly	120	60	10000000.0	10000000.0	0.0			0.00	1.000000	Structural	2	2
M2/2.12.3.A	Longeron Strut Assembly	244	60	10000000.0	10000000.0	0.0			0.00	1.000000	Structural	2	2
FT.36	Thermal Coatings - Clean	1	1	43000.0	100000000.0	0.0		15.00	0.00	1.000000	Structural	2	2
FT.01	1/2 inch Key Wrench	1	1	247500.0	175200.0	0.0			0.50	1.000000	Mechanical	2	2
FT.02	7/16 inch socket	1	1	247500.0	175200.0	0.0			0.00	1.000000	Mechanical	2	2
M2/3.12.7.A	Lower Base	1	1	300000.0	21002.0	0.0			0.00	0.002000	Structural	1	1
M2/2.12.3.C.C	MBC Guide Pins	80	52	10000000.0	10000000.0	0.0			0.00	1.000000	Structural	1	1
M2/2.10.3.???	Rot. Joint Motor Cont	0	0	0.0	1602560.0	0.0			0.00	1.000000	Electromech	1	1
M2/2.10.3.???	Rotary Joint Motor Controller	0	0	0.0	1602560.0	0.0			0.00	1.000000	Electrical	1	1
MA.30	TVC Thermal Valve Controller	4	4	87600.0	87600.0	0.0			0.00	0.010000	Electronic	1	1
M2/2.22.4.D.D	Fittings	49	49	10000000.0	10000000.0	0.0			0.00	1.000000	Structmech	1	1
M2/2.21.7.6.A	Berthing Latch Assembly	24	24	500000.0	500000.0	0.0			0.00	0.001000	Electromech	1	1
M2/7.16.5.D	SSS Transmitter-Rec Type 2	4	2	23456.0	60213.0	0.0			0.00	0.050000	Electronic	1	1
M2/3.12.7.D	Lower Base Latch Motor Assy.	4	4	500000.0	102041.0	0.0			0.00	0.002000	Electromech	1	1
M4.03	Beta Gimal Bearing Subassembly	8	8	170995.2	1705112.0	0.0			0.00	1.000000	Mechanical	1	1
M2/2.19.3.A.A	Bearing Assembly	2	32	500000.0	1423905.0	0.0			0.00	1.000000	Mechanical	1	1
M2/5.36.5.A.???	PWP Stanchion	0	4	0.0	153315.0	0.0			0.00	0.007000	Structural	1	1
M2/5.36.9.E	PFR Workstation Stantion	2	4	200320.0	153315.0	0.0			0.00	0.007000	Structmech	1	1
FT.14	Power Module	1	1	99476.0	236295.0	0.0			0.00	1.000000	Electrical	1	1
M2/2.22.3.C.E	Pallet Power Cable Assy. -011	4	8	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1
M2/2.22.3.D.E	Interface Pow.Cable Assy. -011	4	8	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1
M2/2.22.3.C.J	Pallet Power Cable Assy. -021	4	8	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1
AP.4	Payload Interface Adapter(PIA)	0	4	0.0	990640.0	0.0			0.00	1.000000	Electrical	1	1
M2.01	Harness Assy, Shoulder Deploy.	4	4	1000000.0	1000000.0	0.0			0.00	1.000000	Electrical	1	1
ZS.01	Airlock Outer Hatch	1	1	262000.0	262000.0	0.0			0.00	1.000000	Structmech	1	1
M2/3.18.4.C	Motor Drive Electronics	2	2	300000.0	175200.0	0.0			0.00	0.023000	Electronic	1	1
MA.05	Exhaust Nozzle Heater Elem A/L	1	1	69992.4	300000.0	0.0			0.00	1.000000	Electrical	1	1
M2/2.22.3.D.C	Interface Pow.Cable Assy. -007	3	6	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1
M2/5.36.5.???	EV Umbilical	0	2	0.0	70070.0	0.0			0.00	0.007000	Electrical	1	1
FT.29	FTS Umbilical	1	1	1000000.0	87600.0	0.0			0.00	0.100000	Electromech	1	1
SP.43	Power Data Grapple Fixture	6	6	2032500.0	2032500.0	0.0			0.00	1.000000	Electromech	1	1
SP.05	MDD Cable Harness	2	2	694440.0	694440.0	0.0			0.00	1.000000	Electrical	1	1
M4.12.???	Beta Gimble Platform Sub Assy	0	8	0.0	2917167.0	0.0			0.00	1.000000	Mechanical	1	1
M2/7.36.10.???	Rotation/Translation Aid	0	2	0.0	136463.0	0.0			0.00	0.009000	Electromech	1	1
M2/3.12.7.C	Tracking/Rail Coil Luminare	2	2	20900.0	83000.0	0.0			0.00	0.003000	Electronic	1	1
SP.03	Boom Sections	4	4	1666667.0	1666667.0	0.0			0.00	1.000000	Structural	1	1
M2/7.16.6.C	ACS Trans-Recv Amp (ACBSP)	2	2	40271.0	122424.0	0.0			0.00	0.030000	Electronic	1	1
M2/5.36.5.???	EV Umbilical I/F Panel	0	2	0.0	97560.0	0.0			0.00	0.007000	Electrical	1	1
SP.12	Elec Module Cable Harness	22	22	10417000.0	10417000.0	0.0			0.00	1.000000	Structural	1	1
SP.06	Electronic Mod Cable Harness	22	22	10417000.0	10417000.0	0.0			0.00	1.000000	Structural	1	1
M2/2.22.3.C.D	Pallet Power Cable Assy. -009	2	4	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1
M2/2.22.3.D	Pwr.Cable.Port Transv. Bm Tr 1	1	4	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1

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Table 5-1 (continued)

ANALYSIS DATA BASE

	ORU	FP QUANTITY	NEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	ORURELIAB	SAIC Approx. Total	NASA/LEWIS MTTF Total
U2/2.22.3.B	Pwr.Cable.Stbd.Transv. Bm Tr 1	1	4	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	1	1
U2/2.19.6.A.B	Logistics Carrier Wire Harness	10	10	500000.0	500000.0	0.0			0.00	0.000200	Electrical	1	1
U2/3.10.4.D	MDM/EDP Control Electronics	2	2	16300.0	1000000.0	0.0			0.00	0.904000	Electronic	1	1
U2/7.16.7.B.D	SSS Parabolic Antenna Controll	4	4	30000.0	231003.0	0.0			0.00	0.010000	Electronic	0	0
U2/3.12.6.D	Umbilical/Drive Motor Assembly	2	1	100000.0	166536.0	0.0			0.00	0.019000	Electromech	0	0
U2/2.22.4.E.D	Tubing & Fitting Set	26	2	10000000.0	1361000.0	0.0			0.00	1.000000	Mechanical	0	0
SP.20	MBS Cable Harness	1	1	694440.0	694440.0	0.0			0.00	1.000000	Electrical	0	0
U2/3.12.4.A	Turntable Assembly	1	1	200000.0	82777.0	0.0			0.00	0.002000	Electromech	0	0
U2/5.1^ 1.A.D	Hatch Window Assembly	1	1	300000.0	900000.0	0.0			0.00	1.000000	Structural	0	0
BA.01	BMC Berthing Mechanism Control	1	1	87600.0	87600.0	0.0			0.00	0.010000	Electronic	0	0
U2/5.36.5.A.B	PMP Power/data graple fixture	2	2	200320.0	263713.0	0.0			0.00	0.007000	Structmech	0	0
AP.6	Work Attach. Fixture (WAF)	0	1	0.0	876000.0	0.0			0.00	1.000000	Electrical	0	0
AP.5	Multiple Payload Adaptor (MPA)	0	1	0.0	876000.0	0.0			0.00	1.000000	Electrical	0	0
U2/7.16.6.D	S-Band TDRSS Ant Ass (ACANT)	2	2	140000.0	261666.0	0.0			0.00	0.050000	Electronic	0	0
FT.17	Regulator/Charger	1	1	333000.0	909091.0	0.0			0.00	1.000000	Electronic	0	0
U3/2.22.3.G	Node 3 & 4 Umb Cable Assy.	1	2	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	0	0
U3/2.22.3.F	Node 2 Umb. Cable Assy. Power	1	2	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	0	0
U2/2.22.3.E	Node 1 Umb. Cable Assy. Power	1	2	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	0	0
U2/2.22.3.C.D	Pallet Power Cable Assy. -005	1	2	1000000.0	1960000.0	0.0			0.00	1.000000	Electrical	0	0
FT.13	FTS Mass Storage Unit	1	1	332000.0	1000000.0	0.0			0.00	1.000000	Electronic	0	0
BA.21	Thermal Insu. - A/L Cylinder	0	1	30000.0	87600.0	1000000.0		100.00	0.00	1.000000	Structmech	0	0
SP.61	Tool Rack	1	1	416667.0	416667.0	0.0			0.00	0.330000	Structural	0	0
BA.10	Joint Mechanism	6	6	87600.0	87600.0	1000000.0			0.00	0.050000	Electromech	0	0
U2/3.3.3.A.A.J	APA Harness Assy	0	40	0.0	47943000.0	0.0			0.00	1.000000	Structural	0	0
FT.12	EECM Removable Half	2	2	248000.0	2500000.0	0.0			0.00	1.000000	Mechanical	0	0
FT.22	Selector/Camera Control Control	1	1	500000.0	333333.0	0.0			0.00	0.100000	Electronic	0	0
FT.05	COMS Module	1	1	79501.0	352113.0	0.0			0.00	0.100000	Electrical	0	0
U2/5.36.5.B.A	Port. Recon. Station Structure	2	2	1000000.0	407329.0	0.0			0.00	0.005000	Structural	0	0
SP.66	Roll/Yaw Joint Housing	4	4	5425300.0	5425300.0	0.0			0.00	1.000000	Structural	0	0
ES.19	Viewport - Dark Cover	1	1	267000.0	262000.0	0.0			0.00	0.100000	Mechanical	0	0
U2/7.16.8.C	GPS Antenna	3	2	200000.0	1317542.0	0.0			0.00	0.500000	Electronic	0	0
SP.03	MMD Structure	1	1	1666667.0	1666667.0	0.0			0.00	1.000000	Structural	0	0
SP.08	MBS Structure	1	1	1666667.0	1666667.0	0.0			0.00	1.000000	Structural	0	0
SP.70	SPDM Lower Body Segment	1	1	1666667.0	1666667.0	0.0			0.00	1.000000	Electromech	0	0
SP.76	SPDM Upper Body Segment	1	1	1666667.0	1666667.0	0.0			0.00	1.000000	Electromech	0	0
U2/3.12.5.A	Track Base Assembly	1	1	500000.0	409065.0	0.0			0.00	0.015000	Electromech	0	0
SP.40	Pitch Joint Housing	3	3	5425300.0	5425300.0	0.0			0.00	1.000000	Structural	0	0
FT.21	TR Redundant Controller	1	1	266000.0	500000.0	0.0			0.00	0.100000	Electronic	0	0
FT.19	Storage Unit Controller	2	2	456000.0	4000000.0	0.0			0.00	1.000000	Electronic	0	0
SP.37	PDGF	1	1	2032500.0	2032500.0	0.0			0.00	1.000000	Electromech	0	0
U4.05	Beta Gimbal Trans Structure	0	0	260697.6	16666600.4	0.0			0.00	1.000000	Structural	0	0
SP.63	Tools	1	1	833333.0	833333.0	0.0			0.00	0.330000	Mechanical	0	0
SP.62	Tools	1	1	833333.0	833333.0	0.0			0.00	0.330000	Mechanical	0	0
SP.68	Type 1 SSRMS Cable Harness	4	4	10417000.0	10417000.0	0.0			0.00	1.000000	Structural	0	0
SP.69	Type 2 SSRMS Cable Harness	4	4	10417000.0	10417000.0	0.0			0.00	1.000000	Structural	0	0
SP.41	Pitch Joint Housing	2	2	5425300.0	5425300.0	0.0			0.00	1.000000	Structural	0	0
SP.67	Roll/Yaw Joint Housing	2	2	5425300.0	5425300.0	0.0			0.00	1.000000	Structural	0	0
U2/2.12.4.C	MSC Umbilical Supports	6	13	10000000.0	40000000.0	0.0			0.00	1.000000	Structural	0	0
U2/5.36.5.A.???	Temp Eqp Restraint Aid (TERA)	0	2	0.0	1111111.0	0.0			0.00	0.007000	Structmech	0	0
U2/5.35.5.1.???	A/L External Cables -Assy 2	0	6	0.0	23373300.0	0.0			0.00	1.000000	Structural	0	0
SP.78	Wiring Harness - Body	2	2	10417000.0	10417000.0	0.0			0.00	1.000000	Structural	0	0
SP.65	Roll Joint Housing (Neck)	1	1	5425300.0	5425300.0	0.0			0.00	1.000000	Structural	0	0
U2/5.36.5.A.???	PMP Base	0	2	0.0	1996000.0	0.0			0.00	0.007000	Structmech	0	0
U2/5.35.5.1.A	A/L External Cables -Assy 1	1	6	750000.0	36282520.0	0.0			0.00	1.000000	Structural	0	0
U2/5.36.5.B.???	PCD Mounting and Interface	0	2	0.0	1470500.0	0.0			0.00	0.001000	Electromech	0	0
U2/2.12.4.B	EVA Trans Syst Rail & Supports	1	1	10000000.0	10000000.0	0.0			0.00	1.000000	Structmech	0	0

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ANALYSIS DATA BASE

	ORU	FP QUANTITY	OEM QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	COMRELIAB	SAIC Approx. Total	NASA/LEWIS MTTF Total
U2/3.1207	Harness Assembly, Upper	1	2	300000.0	27114000.0	0.0			0.00	1.000000	Structural	0	0
UA.19	TV Camera Assembly	3	3	43000.0	43000.0	10000000.0			0.00	0.050000	Electromech	0	0
FT.24	Worksite Attach Mech (Bus NF)	1	1	39791.0	6666667.0	0.0			0.00	0.100000	Electromech	0	0
U8/3.12.5.???	Truss Boom Cable Tray Harness	0	2	0.0	51900000.0	0.0			0.00	1.000000	Structural	0	0
U2/2.12.5.A.6	IUSP Pallet Micro Protection	2	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.A.8	IUSP Pallet Insulation Set	2	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.0	Stb'd. TCS Radiator Pallet Ins	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.L	Port TCS Radiator Pallet Insul	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.K	Port TCS Radiator Pallet Micro	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.N	Stb'd. TCS Radiator Pallet Mic	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.D	IUSP Pallet Micro Protection	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.C	IFSP Pallet Insulation Set	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.G	GN & C Pallet Micro Protection	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/2.12.5.H	GN & C Pallet Insulation Set	1	1	10000000.0	40000000.0	0.0			0.00	1.000000	Structmech	0	0
U2/3.12A?	Harness Assembly, Lower	1	2	250000.0	91500000.0	0.0			0.00	1.000000	Structural	0	0
U4.06	Beta Gimbal Assy A/B	0	0	131400.0	300000030.0	0.0			0.00	1.000000	Structural	0	0
U4.17	IEA Transition Structure	4	4	260697.0	249999375.0	0.0			0.00	1.000000	Structural	0	0
FT.27	Power Data Grapple Fixture	1	1	1000000.0	25000000.0	0.0			0.00	0.100000	Electromech	0	0
FT.23	Worksite Attach Mech (MAF)	1	1	40000.0	25000000.0	0.0			0.00	0.100000	Electromech	0	0
U2/7.36.10.???	EVA Tool Kit	0	2	0.0	1035.0	100000000.0			0.00	0.000000	Mechanical	0	0
FT.14.1	Manipulator Life Change	2	0	87600.0	87600.0	0.0			0.00	1.000000	Electromech	0	0
FT.09.1	Caution & Warn Device Change	3	0	17520.0	17520.0	0.0			0.00	1.000000	Electrical	0	0
FT.07.1	CPA Life Change	1	0	43000.0	43000.0	0.0			0.00	1.000000	Electronic	0	0
FT.08.1	Contamination Sen Life Change	4	0	43000.0	43000.0	0.0			0.00	1.000000	Electronic	0	0
FT.06.1	Cameras (Clean Lens)	4	0	43000.0		0.0			0.00	1.000000	Electromech	0	0
FT.03.1	ASPS Life Change	1	0	876000.0		0.0			0.00	1.000000	Electromech	0	0
FT.04.1	Batteries Life Change	3	0	17520.0	17520.0	0.0			0.00	1.000000	Electrical	0	0
U2.23	Instrumentation Assembly	2	0	300000.0		0.0			0.00	1.000000	Electronic	0	0
U2/2.19.4.A.E	Relubricator Mechanism	2	0	1000000.0		0.0			0.00	1.000000	Electromech	0	0
U2.20	Harness Assy, Wrist Joint	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.4.A.B	Instrumentation Package	2	0	250000.0	250000.0	0.0			0.00	1.000000	Electronic	0	0
U2.19	Harness Assy, Wrist Boom	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.4.A.E	Locking Mechanism	2	0	99423.0	99423.0	0.0			0.00	1.000000	Electromech	0	0
U2.18	Harness Assy, Up Radial Joint	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.3.A.B	Encoder	2	0	2000000.0		0.0			0.00	1.000000	Electromech	0	0
U2.17	Harness Assy, Shoulder Joint	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.3.A.E	Relubricator Mechanism	2	0	1000000.0		0.0			0.00	1.000000	Electromech	0	0
U2.16	Harness Assy, Shoulder Boom	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.3.A.D	Engage/Disengage Mechanism	4	0	99423.0	99423.0	0.0			0.00	1.000000	Electromech	0	0
U2.15	Harness Assy, Low. Radial Boom	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.17.5.3.A	Alpha/Radiator Joint Elec	0	0	50000.0	50000.0	0.0			0.00	1.000000	Electronic	0	0
U2.14	Harness Assy, Linear Boom Depl	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2.35	Tank Inlet Control Assembly	2	0	300000.0		0.0			0.00	1.000000	Electromech	0	0
U2/2.20.5.A.A	RMG Inlet Pressure Sensor Assy	1	0	300000.0		0.0			0.00	1.000000	Electromech	0	0
U2.31	Pressure Bleed Assembly	2	0	700000.0		0.0			0.00	1.000000	Mechanical	0	0
U2.13	Harness Assy, Linear Boom	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.4.A.D	Engage/Disengage Mechanism	4	0	99423.0	99423.0	0.0			0.00	1.000000	Electromech	0	0
U2/2.20.5.A.C	RMG Inlet Pressure Sensor Assy	2	0	300000.0	300000.0	0.0			0.00	1.000000	Electromech	0	0
U2/2.19.6.A	TRRJ Assembly	2	0	750000.0		0.0			0.00	1.000000	Electromech	0	0
U2.12	Harness Assy, Elbow Joint	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
U2/2.19.6.A.D	Leg Carrier Latch Umb. Control	10	0	300000.0		0.0			0.00	1.000000	Electronic	0	0
U2.06	Drive Module, Deployment Joint	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
U2.37	Waste Gas Dump Assembly	1	0	300000.0		0.0			0.00	1.000000	Electromech	0	0
U2/2.20.5.A.6	RMG Discharge Filter Assembly	1	0	300000.0		0.0			0.00	1.000000	Mechanical	0	0
U2.26	Interconnect Valve Assembly	1	0	300000.0	300000.0	0.0			0.00	1.000000	Electromech	0	0
U2/2.19.3.A.6	Instrumentation Package	2	0	250000.0	250000.0	0.0			0.00	1.000000	Electronic	0	0

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Table 5-1 (continued)

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ANALYSIS DATA BASE

	ORU	FP QUANTITY	SEM QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	CHURELIAB	SAIC Approx. Total	NASA/LEWIS MTTF Total
W2/2.19.3.A	Solar Alpha Rotary Joint Assy.	2	0	750000.0		0.0			0.00	1.000000	Electromech	0	0
W2.34	Tank Discharge Control Assy	2	0	300000.0		0.0			0.00	1.000000	Electromech	0	0
W2/2.19.4.A.J	Radiator Boom Assembly	2	0	250000.0	250000.0	0.0			0.00	1.000000	Structural	0	0
W2.05	Drive Electronics	2	0	14062.0	14062.0	0.0			0.00	1.000000	Electronic	0	0
W1.12.1	MLI (FWD Trun & Keel Pa) Chang	10	0	87600.0	87600.0	0.0			0.00	1.000000	Structmech	0	0
W1.11.1	MLI (Long & Aft Trun) Change	12	0	87600.0	87600.0	0.0			0.00	1.000000	Structmech	0	0
W2/2.20.5.B.A	NMG Inlet Pressure Sensor Assy	1	0	300000.0		0.0			0.00	1.000000	Electromech	0	0
W1.10.1	M/D Shield Changeout	246	0	87600.0	87600.0	0.0			0.00	1.000000	Structmech	0	0
W2/3.3.3.A.A.B	Drive Module, Linear Joint	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/3.3.3.A.A.G	Drive Module, Wrist Joint	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/5.19	Crowlock Hatch Assembly	1	0	300000.0		0.0			0.00	1.000000	Structmech	0	0
W2/3.10.6.C	Connector Assembly	2	0	1000000.0		0.0			0.00	1.000000	Mechanical	0	0
W2/4.14.3.A	Line Heater Strip	2	0	15000.0	15000.0	0.0			0.00	1.000000	Electrical	0	0
W2/3.10.6.B	Drive Assembly	2	0	300000.0	300000.0	0.0			0.00	1.000000	Electromech	0	0
W2/3.10.5.D	Harness/Diode/Umbil Assy., 150	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/4.14.5.B	Thermal Insulation Strip	1	0	30000.0	30000.0	0.0			0.00	1.000000	Structmech	0	0
W2/3.10.5.A	Harness Assy SPDA Load Conv.	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.6.D	Umbilical Mechanism Harness	2	0	1000000.0		0.0			0.00	1.000000	Electromech	0	0
W2/3.10.4.A	Location/Position Mea Device	2	0	300000.0	300000.0	0.0			0.00	1.000000	Electronic	0	0
W2/3.10.6.A	Connector Mechanism Assy.	1	0	1000000.0		0.0			0.00	1.000000	Mechanical	0	0
W2/3.3.3.A.A.E	Drive Module, Elbow Joint	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/3.3.3.A.A.C	Drive Module, Shoulder Joint	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/3.3.3.A.A.D	Deployment Assembly, Shoulder	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/3.10.6	Umbilical Assy	2	0	157095.0	157095.0	0.0			0.00	1.000000	Electromech	0	0
W2/2.7.13.0.???	MDM-SC (Pallet 3)	2	0	16380.0	16380.0	0.0			0.00	1.000000	Electronic	0	0
W2/3.10.5.F	Harness Assy SPDA to MRS Sim	2	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.5.H	Cable Assy - SPDA to MDM	1	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.5.E	Harness Assy SPDA to C & T	10	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/2.22.4.A.J	Temperature Sensor	12	0	600000.0		0.0			0.00	1.000000	Electronic	0	0
W2/3.10.5.D	Harness Assy SPDA to Payload	2	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/2.22.3.F	Pwr.Cable.Stbd.Transv. Bm Tr 2	1	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.5.C	Harness/Umbil Assy Pwr OMS SPD	4	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.5.K	Cable Assy - SPDA to PDGF	1	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/2.21.7.6.D	Prop. Latch & Umbilical Cont	0	0	500000.0		0.0			0.00	1.000000	Electronic	0	0
W2/3.10.3.B	Harness Assy - COAX	10	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/7.13.3.A	Bus Network Inter Unit (BINU)	5	0	39000.0	39000.0	0.0			0.00	1.000000	Electronic	0	0
W2/3.10.5.L	Cable Assy SPDA Motor Control	1	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/2.22.3.E	Pwr.Cable.Port Transv. Bm Tr 2	1	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.5.I	Harness Assy - Fiber Optic	0	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/3.10.5.G	Harness Assy Payload/Subsystem	2	0	1000000.0		0.0			0.00	1.000000	Electrical	0	0
W2/2.22.4.A.I	H2O Interconnect Line Heater	4	0	100000.0	100000.0	0.0			0.00	1.000000	Electrical	0	0
W2/2.20.7.D	Load Converter	4	0	30000.0	30000.0	0.0			0.00	1.000000	Electrical	0	0
W2/2.20.7.B	Electrical Harness (Pallet)	3	0	500000.0		0.0			0.00	1.000000	Electrical	0	0
W2/2.20.5.B.F	NMG Discharge Filter Assembly	1	0	300000.0	300000.0	0.0			0.00	1.000000	Mechanical	0	0
W2/7.13.0.A.E	MDM/MS	35	0	50964.0	50964.0	0.0			0.00	1.000000	Electronic	0	0
W2/7.13.0.B.G	MDM/SC	15	0	16380.0	16380.0	0.0			0.00	1.000000	Electronic	0	0
W2/2.20.5.B.C	NMG Inlet Pressure Sensor Assy	2	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/3.10.4.B	Sec Pwr Distrib Assy (SPDA)	2	0	300000.0	300000.0	0.0			0.00	1.000000	Electrical	0	0
W4.23	PV Utility Plate Type 1	0	0	72443.2	72443.0	0.0			0.00	1.000000	Electromech	0	0
W2/7.14.5.H	Filter Assembly	0	0	21820.0	21820.0	0.0			0.00	1.000000	Mechanical	0	0
W4.13	Electrical Junction Box	0	0	262000.0	262000.0	0.0			0.00	1.000000	Electrical	0	0
W2/9.40.6.C.A	Umbilical Service Set Node 4	1	0	350000.0		0.0			0.00	1.000000	Electromech	0	0
W2/7.14.5.I.B	Dump Tank	1	0	125000.0	12500.0	0.0			0.00	1.000000	Mechanical	0	0
W2/9.40.5.C.A	Umbilical Service Set Node 3	1	0	350000.0		0.0			0.00	1.000000	Electromech	0	0
W4.24	PV Utility Plate Type 2	24	0	79270.0	79270.0	0.0			0.00	1.000000	Electromech	0	0
W2/9.40.4.C.A	Umbilical Service Set Node 2	1	0	350000.0		0.0			0.00	1.000000	Electromech	0	0

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Table 5-1 (continued)

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ORU		FP QUANTITY	NEW QUANTITY	FP MTBF	REVIEW MTBF	SAIC RE-ESTIMATED MTBF	LOW LIFE LIMIT	LIFE LIMIT	HIGH LIFE LIMIT	DUTY CYCLE	COMMODITY	SAIC Approx. Total	NASA/LEWIS UTTF Total
W2/9.00.4.???	Heat Exchanger Node 2	1	0	20500000.0		0.0			0.00	1.000000	Mechanical	0	0
W2/9.00.3.???	Heat Exchanger Node 1	1	0	20500000.0		0.0			0.00	1.000000	Mechanical	0	0
W3/7.14.0.0	Module Support Structure	24	0	300000.0	500000.0	0.0			0.00	1.000000	Structural	0	0
W3/9.12.5.0	Exterior Window Cover Set, Cup	2	0	100000.0	100000.0	0.0			0.00	1.000000	Electromech	0	0
W2/9.00.5.???	Heat Exchanger Node 3	1	0	20500000.0		0.0			0.00	1.000000	Mechanical	0	0
W2/7.16.0.C	GPS Low Noise Amplifier	3	0	200000.0	200000.0	0.0			0.00	1.000000	Electronic	0	0
W3/9.00.6.???	Heat Exchanger Node 4	1	0	20500000.0		0.0			0.00	1.000000	Mechanical	0	0
*** Total ***		5654	0153										

*1

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5.4. Life Limited ORUs.

5.4.1. Characterization of Life Limits.

One of the important differences between our study and the previous EMTT analysis is the collection of separate statistics for a constant, random MTBF and for an expected life limit. Like MTBFs, life limits were provided by the engineers working on the ORU design at the various Work Package sites. The life limits were often based on rough estimates of degradation caused by the environment (e.g., atomic oxygen, micrometeroids), equipment duty cycle and wear-out. These life limits appear to be objectively estimated from the available information, and should be viewed as an initial estimate. Although these estimates should be refined as the design progresses, for many ORUs the most significant change to the life limit estimates will come from performance monitoring in space. The performance of these components can potentially be monitored by inspection measurement or instrumentation. The ability (or inability) to monitor each ORU for precursors to the major failure modes was identified during discussions between SAIC reliability analysts and ORU developers.

Collecting information on component life limits is necessary because many ORUs cannot be expected to last the life of the space station due to of identifiable, predictable and sometimes defensible causes. The expected useful life, as well as the associated uncertainty, was incorporated into this analysis for components whose reliability can be expected to drop sharply at a certain time (e.g, batteries, thermal shields). Failures and maintenance actions attributable to these phenomena can be predicted, within some uncertainty, and the EVA time can be planned in advance. A related issue, not addressed in this perfectly. This is the more conservative approach in terms of functional reliability; in some cases, the appropriate policy may be to ensure that adequate spares are onboard the SSF and allow the ORU to operate until it reaches failure or a specified level of degradation. Over the life of the SSF this will reduce the number of maintenance activities. The decision as to which policy to follow should be made on an ORU-by-ORU basis.

Table 5.2 lists all the ORUs that SSF designers reported to have life limits of less than 30 years. Therefore, we assume that all other external ORUs can be expected to last the life of the Space station, in the absence of of a random failure.

5.4.2 Effect of Multiple Life-limits and Replacements.

Notice that the most common life-limits given (Table 5.2) for the various components are 2, 5 and 10 years. This will cause the amount of time spent performing repairs and/or replacements of these ORUs to peak at years which are multiples of two or more of these expected life limits. Figure 5.2 shows, in a generic sense, that this effect could cause peaks in EVA activity throughout the life of the SSF. The largest expected peak is currently expected to occur over a 3 year time frame centered around year 2015, 20 years into the life of SSF.

The widths of the triangles in Figure 5.2 pictorially represent our estimate of the variation around the best estimate of life limit. The variation around the life limit estimate used in the analysis is assumed to be 6 months in each chronological direction for the ORUs with lives less than or equal to 10 year, and 1 year in either direction for those with lives greater than 10 years. The heights in the figure are hypothetical, but they were quantified with actual data in the failure-rate-versus-time simulations discussed in section 5.7. This issue was investigated in a recent IEEE paper*, which used similar mean-to-variance ratios and predicted that this cyclic function will eventually "damp out" in 10 to 20 generations (i.e., failure and replacement cycles) for reasons discussed below. There are not enough generations to 'damp out' the cyclic effects of most of the life limits in the assumed 30 year life of the SSF. Only the effects of the 2 year life times (and to some degree the 5 year life) are expected to be significantly damped out. The simulation results (Section 5.7) confirm this.

The gradual elimination of the broad swings in facility failure rates associated with end-of-life equipment replacements discussed in the reference and observed in many long term operating facilities arises from several factors:

(1) Limited-life items are rarely replaced exactly at their nominal life limits. Many life-limited items degrade gradually and still perform acceptably although their design lives have expired. On the other hand, it may be convenient or economical to replace some items before nominal end-of-life. Thus replacement is often advanced or deferred by a considerable fraction of the design life of the item involved.

(2) Limited-life items experience non-life-limit failures at indeterminate times other than end of life, at which point they are replaced or repaired "as good as new", or nearly so.

* Grosh, D. L. and Lyon, R. L., "Stabilization Of Wearout - Replacement Rate", IEEE Transactions On Reliability, Vol. R - 24, No.4, Oct. 1975.

Limited Life Item Effect on ORU Failures

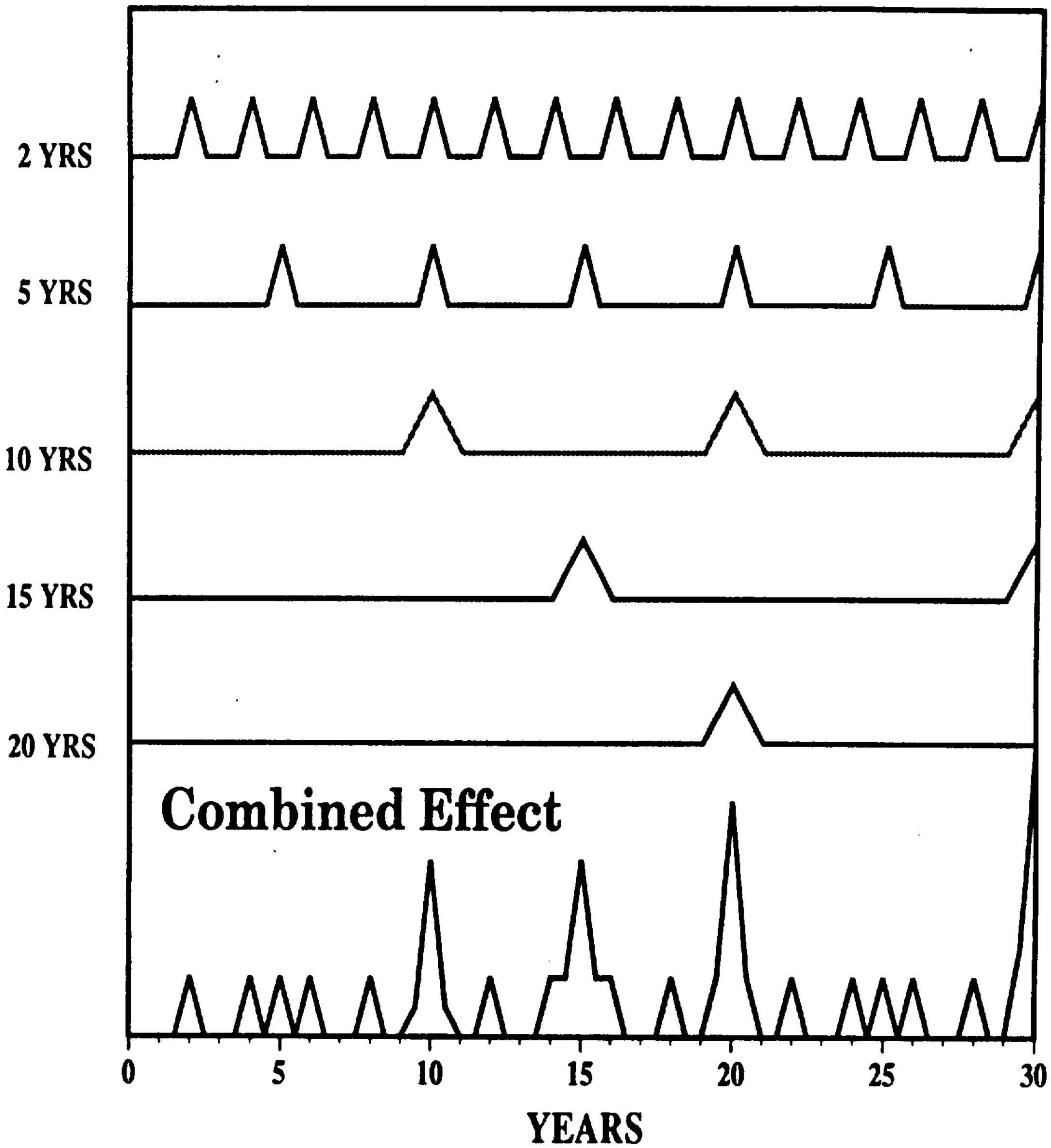

Figure 5.2

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TABLE 5.2 ORUs IDENTIFIED AS HAVING LIFE LIMITS LESS THAN 30 YEARS

Number	Name	Quantity	Life Limit
FT.03	Stabilizer ASPS	1	15.00
FT.04	Battery (20Ah) (Thermal Cont)	3	4.00
FT.06	CPA Camera	2	11.10
FT.07	Camera Positioning Assy (CPA)	1	15.00
FT.08	Contamination Sensor	4	5.00
FT.09	Crew Warning Device	4	11.10
FT.10	Double V-block Tool	2	5.00
FT.11	EECM Holster	2	10.00
FT.14	Manipulator	2	10.00
FT.15	Parallel Jaw Holster	2	10.00
FT.18	Rotary Tool Holster	2	10.00
FT.28	Antenna Assembly	2	15.00
FT.30	FTS Umbilical Storage Holster	1	10.00
FT.31	Module Service Tool (MST)	1	5.00
FT.32	Radiator Panel Tool (RPT)	1	5.00
FT.33	Node Attachment Tool (NAT)	1	5.00
FT.34	Radiator Panel Tool Holster	1	10.00
FT.35	Camera Lamps	8	11.10
FT.36	Thermal Coatings - Clean	1	15.00
NA.04	End Effector	1	10.00
NA.06	FAU Freon Accumulator Unit	2	10.00
NA.07	FPP Freon Pump Package	2	10.00
NA.11	MLI	1	5.00
NA.12	Main Arm Mechanism	1	10.00
NA.17	Small Fine Arm	1	10.00
NA.27	Window Pane	3	10.00
NA.29	Bumper (ELM-PS)	1	10.00
NA.34	MLI of EF	40	10.00
NA.35	EEU (Equip. Exchange Unit)	13	10.00
W4.01	BCDU	24	15.00
W4.02	Battery Subassembly	48	6.50
W4.04	Beta Gimbal Assy (IN-SITU)	8	15.00
W4.07	DCSU	8	15.00
W4.08	DDCU (12.5 Kw)	32	15.00
W4.09	DDCU-IEA	4	15.00
W4.12	Beta Gimbal Drive Motor Cont	8	15.00
W4.15	IEA (IN-SITU)	4	15.00
W4.18	MBSU - ITA	4	15.00
W4.21	PV Blanket & Box (L & R)	16	15.00
W4.25	PVCU	8	15.00
W4.26	Pump	8	15.00
W4.27	RPC Type 1 (10 A)-/Telerob.	75	20.00
W4.29	RPC Type 2 (25 A)-/Telerob.	9	20.00
W4.31	RPC Type 3 (50 A)-/Telerob.	29	20.00
W4.33	RPC Type 4-/(130 A)-/Telerob.	37	20.00
W4.37	SSU	8	15.00

TABLE 5.2 ORUs IDENTIFIED AS HAVING LIFE LIMITS
LESS THAN 30 YEARS (cont.)

Number	Name	Quantity	Life Limit
ES.05	External Camera	4	2.00
ES.06	External Light	12	2.00
AP.2	+X ORU	4	3.00
W1.10	M/D Shield	246	10.00
W2/2.12.7.???	EVA Floodlight	30	9.00
W2/2.12.7.???	Fixed Ext Lights	8	9.00
W2/2.12.7.D	EVA Luminare	8	9.00
W2/2.12.7.H	Video Camera Luminare	8	18.00
W2/2.19.4.A.G	Fluid Coupler	2	10.00
W2/2.20.5.A.D	RWG Compressor Asembly	2	10.00
W2/2.20.5.A.F	RWG Dryer Assembly	2	5.00
W2/2.20.5.B.D	MWG Compressor Assembly	2	10.00
W2/2.20.5.B.E	MWG Dryer Assembly	2	5.00
W2/3.18.4.???	Trans. Ener Stor Sys (TESSO)	4	10.00
W2/4.21.6.A	Resistojet Module	4	20.00
W2/5.19.3.A.H	Seal Set	1	7.50
W2/5.35.4.A.D	Depress Disp. Cont. Pnl (EXT)	6	10.00
W2/5.36.4.???	EV charged Part Dir Spect	1	3.00
W2/5.36.5.B.C	Contamination Removal Unit.	2	10.00
W2/5.36.6.B	Portable Work Platform Stowage	2	10.00
W2/5.36.9.???	CETA Tether Shuttle	1	10.00
W2/5.36.9.C	Safety Tether Reels	4	10.00
W2/5.36.9.D	Portable Foot Restraints PFRs	4	10.00
W2/5.36.9.H	CETA Manual Cart	1	10.00
W2/5.36.9.J	Clothesline Assembly	2	10.00
W2/7.14.4.E	Radiator Panel	88	10.00
W2/7.14.5.???	Pressure Reducing Station	2	10.00
W2/7.14.5.A	Pump Assembly	8	10.00
W2/7.14.5.B	Pressure Regulator Ammonia	4	10.00
W2/7.14.5.C	Accumulator	4	10.00
W2/7.14.5.D	Recirculating Control Valve	4	5.00
W2/7.14.5.G.A	Pressure Regulator (N2)	4	10.00
W2/7.16.4.A	External TV Camera Assembly	8	3.75
W2/7.16.7.B.A	TDRSS Parabolic Ant (SGANT)	2	16.00
W2/7.17.3.A	Star Tracker	3	10.00
W2/7.17.4.A	Inertial Sensor Assembly	3	10.00
W2/7.17.6.A	Control Moment Gyro Assy (CMG)	6	10.00
W2/7.36.10.???	OCSS Controller	2	10.00
W2/7.36.10.???	Pwrd Portable Foot Restraint	4	10.00
W2/7.36.10.???	EVA Tool Storage Device	2	10.00
W2/7.36.10.???	Slidewire	13	10.00
W2/7.36.10.???	Manipulator Foot Restraint	2	10.00
W2/7.36.10.???	O2 Compression and Stroage	2	10.00
W2/7.36.10.???	Misc. EVA Support Equip	2	10.00

(2) Limited-life items experience non-life-limit failures at indeterminate times other thanendof-life, at which point they are replaced or repaired "as good as new", or nearly so.

(3) In both of the above cases, the "clock" on the affected life-limited item is reset at a time other than the expiration of the nominal design life. The accumulation of off-nominal replacement or restoration intervals gradually spreads the peaks in maintenance actions which initially occurred at life-limit intervals, and fills in the intervening valleys.

(4) Limited-life items will become operational throughout the five year construction period of SSF, rather than all starting operation at some arbitrary starting time as in the experiment described in the referenced IEEE paper.*

(5) Finally limited-life items tend to be gradually replaced with longer-lived items in order to reduce maintenance, improve performance, or both. Unless the new life limit is a multiple of the old one, the replacement item no longer contributes to the previous peaks in maintenance load. Although this effect is not included in the study it can be expected to also reduce the peak maintenance loads during the life of SSF.

5.4.3. Results.

For the purposes of ranking the ORUs, the number of life-limit events is calculated by simply calculating the number of life limit cycles that occur in 30 years. For example an ORU with a 5 year life limit would experience 6 cycles in 30 years. The equation for the number of life limit events in 30 years is:

$$N_{Life} = \text{Quantity} \times \frac{30 \text{ years}}{\text{Life-Limit}}$$

This equation slightly overestimates the expected number of life-limit failure events because it neglects the renewal of an ORU following the occurence. Additionally, the total number of life-limit events should be adjusted for ORUs whose final expected life cycle occurs at year 30, in order to take into account the uncertainty in the life limit, and the fact that NASA may not choose to repair slightly degraded ORUs near the end of SSF's life. This affects ORUs whose life limits are exact factors of 30 years (2, 3, 5, 6, 10 and 15 years). Comparing these results to those obtained by random simulation (Section 5.7) indicates that this effect is less than 20% for individual ORUs and essentially zero for the overall totals. The above equation gives a consistent figure of merit that is useful for ranking the ORUs.

* Grosh, et. al., Op. Cit.

Data analysis indicates that SSF will require 2473 repair/replacement events that are attributed to life limits. This averages to about 82 such events per year. The eventual effects on the mission of SSF will generally be somewhat less because of ongoing design changes and the predictable nature of this type of failure event. The predictable nature of life limit mitigates the logistic problems because spare parts can be made available and the EVA can be planned so that multiple repairs can be performed.

5.5. <u>Ranking Of ORUs By Projected Failures</u>

Space Station ORU types are ranked according to their contributions to total number of corrective maintenance actions requiring EVA. The figure of merit for ranking ORU types is an estimate of the total failures that will occur over the 30-year life of *Freedom*. This includes failure events caused both by life-limits and by randomly occurring failures. The paramenters necessary for this calculation are MTBF, life-limit, and on-board quantity for each ORU. The MTBF was chosen in the following order of prefence: (1) the SAIC re-estimate, (2) the numbers supplied by the Work Package/international partner (WP/IP) during the data review, and (3) the WP/IP-supplied number in the EMTT data base. The most current WP/IP estimates of on-board quantity, duty cycle, and life-limit were used.

The basic parameter for ORUs is w(t), or the unconditional failure intensity at time t, which can be more precisely defined as*:

> The probability that a ORU fails per unit time at time t, given that it entered the normal state at time zero.

In other words, the only underlying assumption in this general model is that the component was good as new at time zero. Note that for unrepairable ORUs, w(t) corresponds to the failure density, f(t). However, since we were dealing with EVA repairs, we did not consider ORUs fitting this type of model.

The key parameter is the expected number of failures or W(t) which is defined as:

> Expected number of failures during time (t,t+dt) given that the component entered the normal state at time zero.

The definition of W(t) implies that it is an integral of w(t). Thus, when the failure rate is constant, $\lambda(t)$ is constant and equal to the failure rate, λ_T, the following model should be used for the expected number of failures:

$$w(0,t) = \frac{\lambda\mu}{\lambda+\mu} t + \frac{\lambda^2}{(\lambda+\mu)^2}(1-e^{-(\lambda+\mu)t}) \qquad (1)$$

* Henley, E. J. and Kumato, H, *Reliability Engineering and Risk Assessment*, Prentice Hall, Inc. 1981

where

μ =	1/MTTR
MTTR =	Mean time to repair, measured from the time of failure to the time the equipment is back in service. Note that this includes the logistic time and thus is not generally the MTTR that should be used for EVA estimates.
λ =	Constant failure rate from the equation below.
t =	The time since initial installation (30years)

The net random failure rate was calculated by assuming that the failure rate during the 'off' portion of the duty cycle (known as the standby failure rate) is one tenth of the operating failure rate:

$$\lambda = \frac{\text{duty cycle}}{\text{MTBF}} + (1 - \text{duty cycle}) \times \frac{0.1}{\text{MTBF}}$$

Since the MTTR is much less than the MTBF, the equation for W(0,t) can be closely approximated by λt. Therefore, the number of failure events in thirty years can be estimated as follows:

$$N_{Random} = \text{Quantity} \times \lambda \times 30 \text{ years}$$

N_{Random} and N_{Life} are then added to estimate the total number of failures in 30 years. The advantage of this method is that the random and life-limit failure rates are clearly displayed and tabulated. The disadvantage is that no credit is given for renewal (in terms of life) for ORU replacements that occur following a random failure. The renewal effect is better estimated using the equation provided by NASA Lewis Research Center:

$$\text{MMTF} = \text{MTBF} \times \left(1 - e^{-\left(\frac{\text{LifeLimit}}{\text{MTBF}}\right)} \right)$$

The disadvantage of the Lewis equation is that the life limits that expire at Year 30 can not be easily accounted for. In fhe following tabulation, the result of both approaches are listed. They agree quite closely.

Table 5.3 lists the ORUs in order of decreasing importance to the total failure count, as estimated using SAIC's approximate method. The lower portion of the tables list the total numbers of failures for the ORUs shown on that page. Additionally, the totals for the entire population of external ORUs are repeated on each page. The totals correspond to 231 failures per year, made up of 149 random failures per year and 82 life limit failures per year.

The most important result of this tabulation is the relative ranking of ORU types. The table shows several pages containing the 150 ORU types most important to overall external maintenance. The exact order is not particularly important in that a slight design change or recalculation of reliability parameters could move an ORU type several places in either direction. However, ORUs appearing at any of the first several pages are certainly worthy of attention from designers and planners. ORUs not appearing on the first several pages are not likely to have a large impact on the total number of failures during the SSF mission.

Table 5.3.

Page No. 1 06/21/90 12:06:49 ORUS RANKED BY THE NUMBER OF FAILURES IN 30 YEARS

Rank	ORU Identification		Onboard Quantity	SAIC APPROXIMATION Random	SAIC APPROXIMATION Life Limit	SAIC APPROXIMATION Total	NASA/Lewis MTTF Total	Contribution to Total Failure Count
1.	W1.10	M/D Shield	246	65	615	680	771	9.79%
2.	W2.30	Payload Interface (APAE)	20	354	0	354	354	5.09%
3.	W2/7.14.4.E	Radiator Panel	88	90	220	310	311	4.46%
4.	W4.02	Battery Subassembly	48	72	192	264	260	3.81%
5.	W2/7.13.8.???	MDM (C-10)	48	212	0	212	212	3.05%
6.	ES.06	External Light	12	0	174	174	180	2.51%
7.	W2/2.12.7.???	EVA Floodlight	30	62	90	152	134	2.18%
8.	W2/7.13.8.???	MDM (C-4)	51	141	0	141	141	2.04%
9.	W2/7.16.4.A	External TV Camera Assembly	8	75	60	135	109	1.95%
10.	W4.27	RPC Type 1 (10 A)-/Telerob.	75	46	75	121	137	1.74%
11.	NA.34	MLI of EF	40	11	100	111	125	1.59%
12.	W4.08	DDCU (12.5 Kw)	32	56	48	104	96	1.49%
13.	W4.01	BCDU	24	63	36	99	86	1.43%
14.	NA.18	TV Camera & Light	3	99	0	99	99	1.42%
15.	W2/7.13.8.???	MDM (C-16)	16	91	0	91	91	1.31%
16.	W2/4.21.6.A	Resistojet Module	4	80	4	84	80	1.21%
17.	W1.20	Windows/Trap	12	79	0	79	79	1.13%
18.	W2/7.14.5.A	Pump Assembly	8	54	20	74	60	1.07%
19.	ES.05	External Camera	4	4	58	62	62	0.89%
20.	W4.33	RPC Type 4-/(130 A)-/Telerob.	37	23	37	60	68	0.86%
21.	CD.07	CCTV Camera, Light & PTU Assy	2	58	0	58	58	0.84%
22.	CD.06	CCTV Camera, Light & PTU Assy	2	58	0	58	58	0.84%
23.	CD.56	MBS Thermal Blanket	8	58	0	58	58	0.83%
24.	CD.84	MMD Thermal Blankets	8	58	0	58	58	0.83%
25.	W4.25	PVCU	8	42	12	54	45	0.78%

Table 5.3. (cont.)

Page No. 2 06/21/90 12:06:49 ORUS RANKED BY THE NUMBER OF FAILURES IN 30 YEARS

Rank	ORU Identification	Onboard Quantity	SAIC APPROXIMATION Random	Life Limit	Total	NASA/Lewis MTTF Total	Contribution to Total Failure Count
26. NA.26	CAP (Relief/Vent Dump Valve)	10	53	0	53	53	0.76%
27. W1.14	PRTC Valves	8	53	0	53	53	0.76%
28. CD.08	CCTV Cameras and Lights	2	49	0	49	49	0.70%
29. W4.31	RPC Type 3 (50 A)-/Telerob.	29	18	29	47	53	0.67%
30. W4.26	Pump	8	34	12	46	38	0.66%
31. W2/7.14.5.G.A	Pressure Regulator (N2)	4	32	10	42	34	0.60%
32. CD.64	Upper Body CCTV (Stereo)	1	42	0	42	42	0.60%
33. W2/7.14.5.B •	Pressure Regulator Ammonia	4	31	10	41	34	0.59%
34. AP.2	+X ORU	4	3	38	41	41	0.58%
35. W2/2.12.7.D	EVA Luminare	8	16	24	40	36	0.58%
36. W2/7.16.4.O	External Video Switch	4	39	0	39	39	0.55%
37. CD.11	Dexterous Arm	2	38	0	38	38	0.55%
38. W2/7.36.10.???	Slidewire	13	5	33	37	41	0.54%
39. NA.35	EEU (Equip. Exchange Unit)	13	3	33	36	41	0.52%
40. W2/2.12.7.???	Fixed Ext Lights	8	10	24	34	32	0.49%
41. CD.04	Arm CCTV (With Lights)	2	33	0	33	33	0.48%
42. CD.09	CCTV Cameras and Lights	2	33	0	33	33	0.48%
43. W1.17	Trap Window Shutters	12	32	0	32	32	0.45%
44. W2/7.14.5.D	Recirculating Control Valve	4	9	22	31	29	0.44%
45. W1.15	Shut-Off Valves	28	30	0	30	30	0.43%
46. W2/2.20.3.F.???	N2 Press/vent Safety Assy	2	29	0	29	29	0.42%
47. W2/2.20.3.F	N2 Pressure Sensor Assembly	2	29	0	29	29	0.42%
48. CD.35	Main Body CCTV, Light & PTU	1	29	0	29	29	0.42%
49. W2/2.22.4.A.A	Interconnect Lines	284	29	0	29	29	0.42%
50. W4.07	DCSU	8	17	12	29	26	0.41%
PAGE TOTALS		463	695	246	941	922	13.56%
DATA BASE TOTALS		8158	4469	2473	6942	6940	100.00%

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Table 5.3. (cont)

ORUS RANKED BY THE NUMBER OF FAILURES IN 30 YEARS

Rank	ORU Identification	Onboard Quantity	SAIC APPROXIMATION Random	Life Limit	Total	NASA/Lewis MTTF Total	Contribution to Total Failure Count
51. CD.52	Boom Thermal Blankets	4	29	0	29	29	0.41%
52. CD.72	Roll/Yaw Jnt Hsing Ther Blnkt	4	29	0	29	29	0.41%
54. CD.38	PMDS/DMS Electronics Unit	2	27	0	27	27	0.39%
55. W2/7.16.5.A.A	SSS Omni Antenna	4	27	0	27	27	0.39%
56. W2/2.19.3.A.B	Drive Assembly	4	27	0	27	27	0.39%
57. W2/2.19.4.A.B	Drive Assembly	4	27	0	27	27	0.39%
58. CD.18	IVA INS Hand Controller	2	27	0	27	27	0.38%
59. W4.14	Fluid Junction Box	8	26	0	26	26	0.37%
60. W2/7.14.5.???	Cold Plate Assy	24	25	0	25	25	0.37%
61. CD.28	Latching End Effector (LEE)	2	25	0	25	25	0.36%
62. CD.39	Payload/ORU Accommodation Unit	2	25	0	25	25	0.36%
63. W4.21	PV Blanket & Box (L & R)	16	1	24	25	32	0.36%
64. W2/2.20.5.B.E	MWG Dryer Assembly	2	13	11	24	20	0.35%
65. W2/2.20.5.A.F	RWG Dryer Assembly	2	13	11	24	20	0.35%
66. W2/7.14.3.B.A	Heat Exchanger Units	32	24	0	24	24	0.35%
67. W2/5.36.4.???	EV charged Part Dir Spect	1	13	10	23	18	0.33%
68. W2/2.12.7.???	FTS Luminaire	16	23	0	23	28	0.33%
69. FT.08	Contamination Sensor	4	0	22	22	24	0.32%
70. FT.04	Battery (20Ah) (Thermal Cont)	3	1	21	22	23	0.31%
71. CD.71	Pitch Joint Hsing Ther Blanket	3	22	0	22	22	0.31%
72. W2/7.14.5.???	Pressure Reducing Station	2	16	5	21	18	0.31%
73. W2/2.20.3.???	Outlet Htr/Vent Assy	2	21	0	21	21	0.31%
74. W2/2.12.7.H	Video Camera Luminare	8	13	8	21	21	0.30%
75. CD.21	Joint Drive Unit	7	21	0	21	21	0.30%
PAGE TOTALS		166	492	123	615	604	8.86%
DATA BASE TOTALS		8158	4469	2473	6942	6940	100.00%

Table 5.3. (cont.)

Page No. 4 06/21/90 12:06:49 ORUS RANKED BY THE NUMBER OF FAILURES IN 30 YEARS

Rank	ORU Identification		Onboard Quantity	SAIC APPROXIMATION Random	Life Limit	Total	NASA/Lewis MTTF Total	Contribution to Total Failure Count
76.	AP.3	-X ORU	4	21	0	21	21	0.30%
77.	W2/7.36.10.A	EVA Portable Light Assy	4	5	15	20	5	0.28%
78.	W2/5.36.5.B.B	Port. Contamination Detector	2	20	0	20	20	0.28%
79.	W2/2.19.4.A.G	Fluid Coupler	2	14	5	19	16	0.28%
80.	W4.12	Beta Gimbal Drive Motor Cont	8	7	12	19	20	0.28%
81.	W2/7.17.6.A	Control Moment Gyro Assy (CMG)	6	4	15	19	20	0.27%
82.	W2/3.12C?	Upper Base	1	18	0	18	18	0.26%
83.	W2/2.22.4.F.A	Fluid Control Cable Assembly	135	18	0	18	18	0.26%
84.	W2/5.36.9.A	Handrails	21	18	0	18	18	0.25%
85.	W2/2.20.5.A.D	RWG Compressor Asembly	2	12	5	17	14	0.25%
86.	W2/2.20.5.B.D	MWG Compressor Assembly	2	12	5	17	14	0.25%
87.	W4.18	MBSU - ITA	4	11	6	17	15	0.25%
88.	W4.37	SSU	8	5	12	17	18	0.24%
89.	W2/3.12E?	Upper Base Latch Assembly	4	16	0	16	16	0.23%
90.	W2/9.40.3.C.B	Umbilical Service Set Elec	120	16	0	16	16	0.23%
91.	FT.35	Camera Lamps	8	0	16	16	22	0.23%
92.	ES.08	MDPS cylindrical sections	16	16	0	16	16	0.23%
93.	W2/5.35.4.A.D	Depress Disp. Cont. Pnl (EXT)	6	1	15	16	18	0.23%
94.	W2/2.20.3.A	N2 SC Heater Assembly	2	15	0	15	15	0.22%
95.	CD.20	Joint Drive Unit	5	15	0	15	15	0.22%
96.	W2/7.14.5.???	Relief Valve	28	15	0	15	15	0.21%
97.	W2/7.36.10.???	O2 Compression and Stroage	2	10	5	15	12	0.21%
98.	CD.23	Joint Electronics Unit (JEU)	14	15	0	15	15	0.21%
99.	W4.29	RPC Type 2 (25 A)-/Telerob.	9	5	9	14	16	0.21%
100.	W2/7.16.4.???	Video Interface Converter	4	14	0	14	14	0.21%
	PAGE TOTALS		417	303	120	423	407	6.09%
	DATA BASE TOTALS		8158	4469	2473	6942	6940	100.00%

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Table 5.3. (cont.)

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ORUS RANKED BY THE NUMBER OF FAILURES IN 30 YEARS

Rank	ORU Identification		Onboard Quantity	SAIC APPROXIMATION Random	Life Limit	Total	NASA/Lewis MTTF Total	Contribution to Total Failure Count
101.	CD.74	PJH (B & U) Thermal Blanket	2	14	0	14	14	0.21%
102.	CD.73	Roll/Yaw Jnt Hsng Ther Blanket	2	14	0	14	14	0.21%
103.	W1.02	Interface Assembly	8	14	0	14	14	0.20%
104.	FT.10	Double V-block Tool	2	3	11	14	14	0.20%
105.	W4.15	IEA (IN-SITU)	4	8	6	14	9	0.20%
106.	W2/7.14.5.C	Accumulator	4	4	10	14	14	0.20%
107.	W2/7.17.4.A	Inertial Sensor Assembly	3	6	8	13	12	0.19%
108.	NA.16	Seal-Airlock Pressure Equal.	1	13	0	13	13	0.19%
109.	NA.15	Seal Airlock Outer Hatch	1	13	0	13	13	0.19%
110.	W1.19	Windows/Round	2	13	0	13	13	0.19%
111.	W4.09	DDCU-IEA	4	7	6	13	12	0.19%
112.	W2/2.22.4.C.A	Flex Hose	77	13	0	13	13	0.19%
113.	W2/3.18.4.???	Trans. Ener Stor Sys (TESSO)	4	3	10	13	13	0.18%
114.	CD.24	LEE - Base	1	13	0	13	13	0.18%
115.	CD.87	LEE	1	13	0	13	13	0.18%
116.	NA.13	PSU EF Power Switching Unit	4	12	0	12	12	0.17%
117.	NA.02	ESC EF System Controller	4	12	0	12	12	0.17%
118.	NA.14	SPC Signal Processing Controll	4	12	0	12	12	0.17%
119.	NA.23	VSW Video Switcher	4	12	0	12	12	0.17%
120.	NA.08	HX for EF	2	12	0	12	12	0.17%
121.	W2/5.36.9.D	Portable Foot Restraints PFRs	4	2	10	12	13	0.17%
122.	W2/2.20.5.A.???	RWG Inlet Vent/Safe Assy	1	12	0	12	12	0.17%
123.	W2/2.20.5.B.???	MWG Inlet Vent/Safe Assy	1	12	0	12	12	0.17%
124.	W2/2.21.7.6.C	Umbilical Mechanism	24	12	0	12	12	0.17%
125.	W2/2.22.3.C.G	Pallet Power Cable Assy. -015	86	12	0	12	12	0.17%
	PAGE TOTALS		250	259	61	320	314	4.61%
	DATA BASE TOTALS		8158	4469	2473	6942	6940	100.00%

Table 5.3. (cont.)

ORUS RANKED BY THE NUMBER OF FAILURES IN 30 YEARS

Rank	ORU Identification		Onboard Quantity	SAIC APPROXIMATION Random	Life Limit	Total	NASA/Lewis MTTF Total	Contribution to Total Failure Count
126.	W2/7.36.10.???	Pwrd Portable Foot Restraint	4	1	10	11	13	0.17%
127.	W2/5.36.9.C	Safety Tether Reels	4	1	10	11	13	0.16%
128.	W2/2.22.3.C.A	Pallet Power Cable Assy. -003	82	11	0	11	11	0.16%
129.	FT.14	Manipulator	2	6	5	11	9	0.15%
130.	W2/2.20.5.A.B	RWG Vent/Saftey Assembly	1	11	0	11	11	0.15%
131.	W2/2.20.5.B.B	MWG Vent/Safety Assembly	1	11	0	11	11	0.15%
132.	W2/9.40.3.C.A	Umbilical Service Set Fluid	64	11	0	11	11	0.15%
133.	W2/7.36.10.???	OCSS Pwr Supply	2	3	8	11	3	0.15%
134.	W2/7.16.7.C.A	Ku-Band TDRSS T-R (SGT-R)	4	11	0	11	11	0.15%
135.	W2/2.20.5.A.???	RWG Tank Press Ind Assy	1	11	0	11	11	0.15%
136.	W2/2.20.5.B.???	MWG Tank Press Ind Assy	1	11	0	11	11	0.15%
137.	W1.23	Electrical Junction Box	4	11	0	11	11	0.15%
138.	CD.22	Joint Electronics Unit (JEU)	10	10	0	10	10	0.15%
139.	W2/7.14.4.A	Condenser/Subcooler Module	22	10	0	10	10	0.15%
140.	W2/2.22.4.A.E	Umbilical Flex Hose	61	10	0	10	10	0.15%
141.	NA.31	Airlock Table	1	10	0	10	10	0.14%
142.	ES.18	Viewport Ext Drive Mech	1	10	0	10	10	0.14%
143.	W2/2.12.4.B.E.C	Deployable Util Tray Covers	1480	10	0	10	10	0.14%
144.	W2/9.40.3.C.C	Umb. Svc. Set Attch Panel	8	10	0	10	10	0.14%
145.	CD.81	MMD PMDS/DMS Electronic Unit	2	9	0	9	9	0.13%
146.	W2/7.17.3.A	Star Tracker	3	1	8	9	10	0.13%
147.	NA.22	Thermal Insu. A/L Outer Hatch	1	9	0	9	9	0.13%
148.	ES.02	Airlock Outer Hatch Seal	1	9	0	9	9	0.13%
149.	CD.05	Arm Control Unit (ACU)	2	9	0	9	9	0.12%
150.	CD.48	SPDM Main Cont Computer (MCC)	2	9	0	9	9	0.12%
	PAGE TOTALS		1764	212	40	252	247	3.63%
	DATA BASE TOTALS		8158	4469	2473	6942	6940	100.00%

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5.6. Early-Life Reliability Issues.

5.6.1. Summary of Early-Life Failure Effects.

Experience shows that long-term facilities such as Space Station *Freedom* sustain an uncharacteristically high incidence of equipment failures early in life; the failure rate eventually declines to a lower, relatively stable level. The several factors contributing to the high initial failure rate are known collectively as initialization, and those which gradually mitigate the initialization effects are collected under the name of reliability growth. Still a third major factor will affect the failure-versus-time behavior of the Space Station: the fact that external ORUs will gradually arrive on-Station over several years during construction rather than all at once.

As implied, the initialization and growth factors are mutually antagonistic, and their net effect determines the random-failure-versus-time function early in the life of the facility. Because the effects of initialization and reliability growth are closely linked, and it is difficult to distinguish between them from the available historical information, SAIC has analyzed them as a unit. Gradual ORU build-up, which will tend to delay the impacts of both initialization and reliability growth in time, is treated separately in the analysis and the SAIC failure-rate-versus-time model.

The following paragraphs describe initialization and reliability growth in greater detail. Section 5.6.5 discusses ORU build-up during construction.

It must be emphasized that only random failure rates are considered in the ensuing discussion. Life-limit replacements are dealt with separately, in sections 5.4 and 5.7.4.

5.6.2. Initialization.

Operating facilities invariably experience a period of initialization after startup, during which equipment failures occur at uncharacteristically high rates. In the Space Station case, initialization failures will tend to result from at least the following factors:

(1) Latent design deficiencies,
(2) Fabrication defects below the levels detectable by testing,
(3) Defects induced by launching stresses, and
(4) Defects induced by construction stresses and mishaps.

Initialization failures can be reduced by design, quality control, testing, and construction procedures, but never eliminated.

5.6.3. Reliability Growth.

Based on both ground-based facility and long-term multi-spacecraft constellation experience, the three reliability-growth factors discussed below will gradually bring the initialization period to an end. In combination, they tend to reduce failure rates to a relatively low and stable level.

5.6.3.1. Operational Burn-In.

As time goes by, the probability that a component will encounter a stress more severe than it has already survived becomes steadily lower, assuming a reasonably stable environment. The service history of a wide variety of satellites clearly demonstrates the resulting decline in failure rate. This is an inherent effect which can be considered as a final "burn-in" of the design, and it occurs regardless of whether the spacecraft or other facility is accessible for maintenance.

5.6.3.2. Defect Removal.

In maintainable facilities, dominant equipment failure modes are gradually identified and eliminated, even without significant changes in the design and the equipment complement. Of course, this occurs only in the presence of an effective program to identify recurring problems, determine their root causes, and correct them. Such a program is often a sound investment for a long-term facility, and especially so for Space Station *Freedom*, where repeatedly correcting the same problem will be especially burdensome.

(Unfortunately, a variety of factors typically work against effective defect removal in the manned space flight environment, notably the time-consuming, expensive, but necessary process of man-qualifying new or modified equipment.)

5.6.3.3. Technological Evolution.

Equipment in maintainable facilities tends to be gradually replaced with newer hardware incorporating advanced technology as it becomes available. While these replacements are typically driven by performance or cost rather than reliability, improved facility reliability is frequently a by-product because advanced-technology equipment is usually more reliable than the hardware it replaces.

5.6.4. Combined Effects of Initialization and Reliability Growth.

The US Air Force Rome Air Development Center has recently conducted a study of the operational reliability of 57 Earth satellites of various types and orbits.* (The RADC technical report is reproduced in Appendix T.) The key result is that random spacecraft failure rate declines approximately exponentially with time in orbit, essentially stabilizing after the fourth year, shown in Figure 5.3. (The RADC study considered only failures, and excluded deterministic life-limit effects such as the expenditure of orbital-correction propellants.)

The experience represented by Figure 5.3 incorporates both initialization failures and the "operational burn-in" described in paragraph 5.6.3.1. We consider it a fair representation of the effects these factors will have on Space Station *Freedom*. Howevever, the RADC curve does not include either defect removal or technology evolution, because the satellites RADC studied were not accessible for maintenance and technology upgrading. The latter two effects are difficult to quantify, but it is possible to approximate their effects.

A wide variety of long-term aerospace and ground-based facility experience indicates that defect removal and technological evolution will combine to drive the post-initialization random failure rate for the whole facility down to approximately 2/3 of the failure rate predicted from generic component failure rate data. (The generic failure rate data sets typically used in the aerospace community, e.g. MIL-HDBK-217E and NPRD-3, tend to overstate mid-life failure rates for long-term maintainable facilities, probably because they are derived predominantly from the experience of relatively short-lived equipment and facilities. As a result, the standard generic failure rate data sets under-represent reliability growth relative to initialization for long-term maintainable facilities.) This observation is directly relevant to the prediction of Space Station ORU reliability from Work Package and International Parner data, because the WP/IPs principally used generic reliability data to develop their ORU random failure rate estimates.

The curve in Figure 5.4 illustrates the combined effects of initialization and the reliability growth resulting from operational burn-in, defect removal, and technological evolution. It shows an initially high facility random failure rate declining toward a stable rate equal to 2/3 of the rate predicted from WP/IP data. This is the basis of the early-failure model used in SAIC's failure-rate-versus-time projection for *Freedom*.

* H. Hecht and M. Hecht, "Reliability Prediction for Spacecraft", RADC-TR-85-229, U.S. Air Force Rome Air Development Center, 1985.

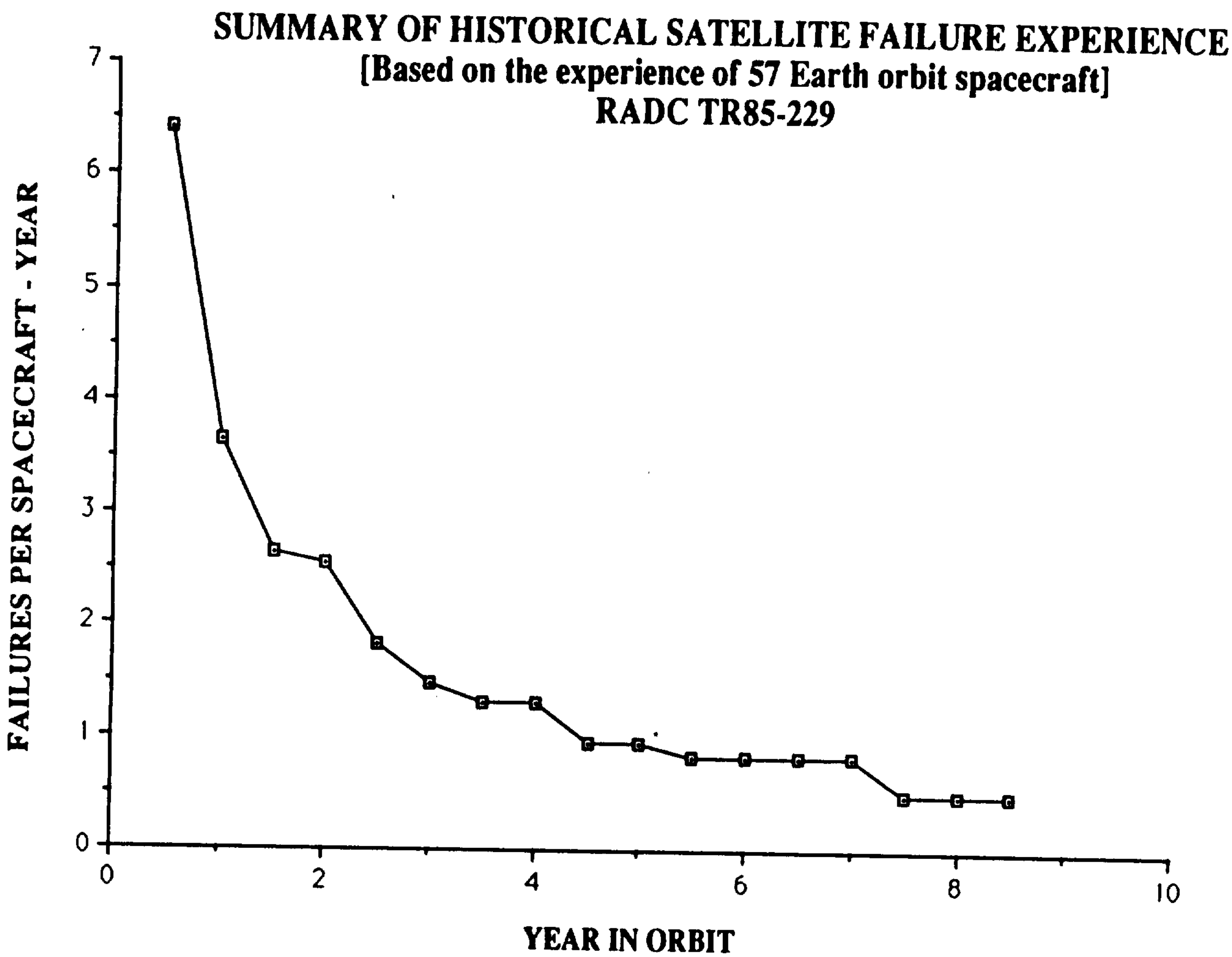
SUMMARY OF HISTORICAL SATELLITE FAILURE EXPERIENCE
[Based on the experience of 57 Earth orbit spacecraft]
RADC TR85-229
FAILURES PER SPACECRAFT - YEAR
7
6
5
4
3
2
1
0
0
2
4
6
8
10
YEAR IN ORBIT

Figure 5.3.

Impact of Historical Spacecraft Failure Rates on Initial ORU Failure Rates

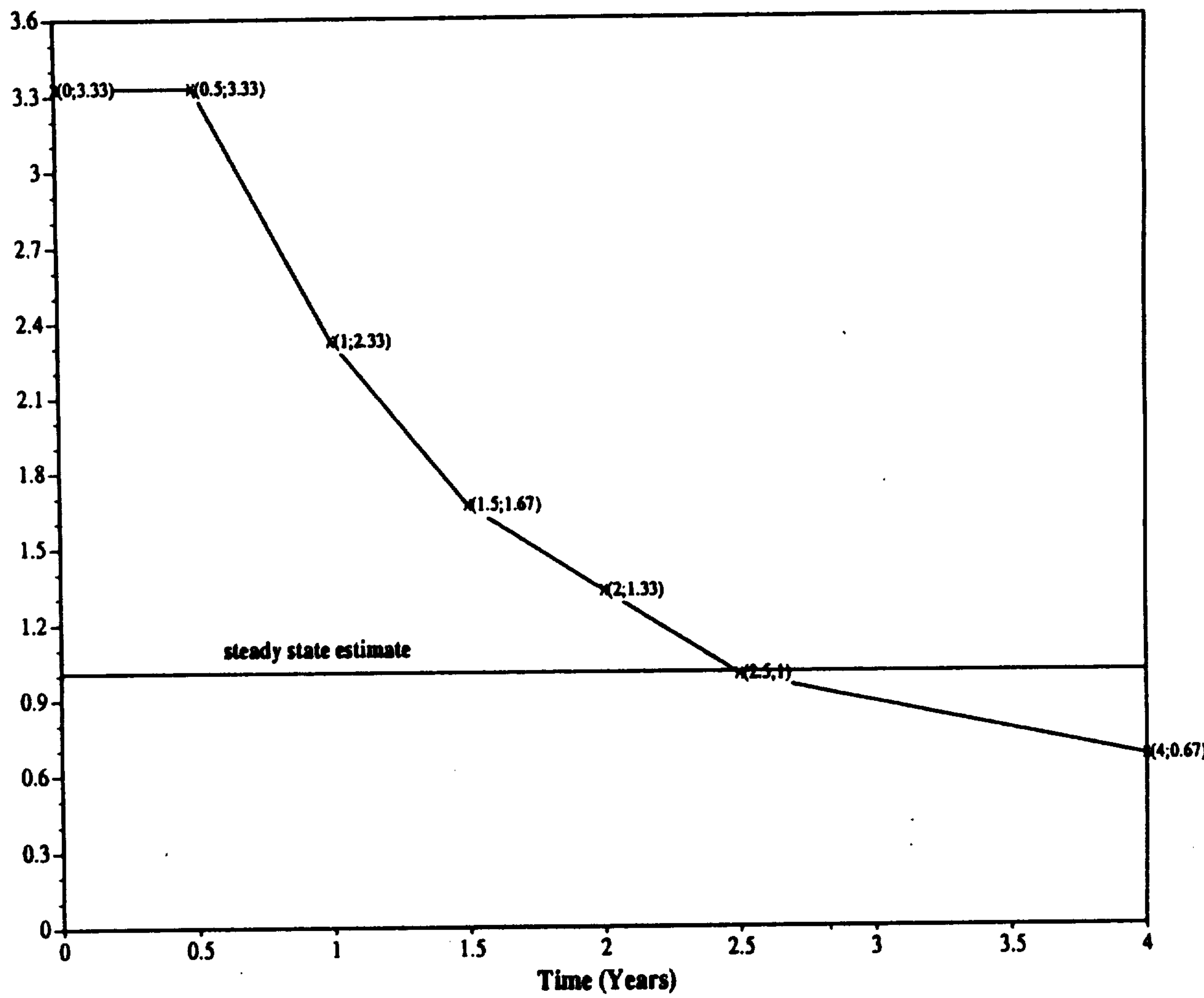

Figure 5.4.

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5.6.5. ORU Build-up During Construction.

The Space Station *Freedom* assembly sequence is expected to be accomplished over 29 STS flights from 3/31/95 through 7/30/99. Various assembly elements are transported during each of these flights. Table 5.4 provides the current Assembly Sequence Overall Manifest Launch Schedule documented in JSC 31000 Vol. 3 Rev. E. SAIC was provided with an estimate of the external ORUs to be launched during each flight by Ocean Systems Engineering. Each of these external ORUs was also classified into one of the following six categories and the approximate percentage of the total is shown:

- Structural-mechanical (38%)
- Electronic (5%)
- Electro-mechanical (10%)
- Electrical (16%)
- Mechanical (15%)
- Structural (16%)

Based on this information SAIC prepared a graphical presentation of these external ORUs by classification for each of the 29 flights (See Figure 5.5)

Some initial observations which can be made from this distribution include the following:

- 42% of the external ORUs are expected to have been installed after the first year of the assembly sequence (i.e., Flights 1 through 4 in 1995)

- 78% of the external ORUs are expected to have been installed after the second year of the assembly sequence (i.e., Flights 5 through 9 in 1996)

- 87% of the external ORUs are expected to have been installed after the third year of the assembly sequence (i.e., Flights 10 through 16 in 1997)

- 90% of the external ORUs are expected to have been installed after the foutth year of the assembly sequence (i.e., Flights 17 through 24 in 1998)

- 99% of the external ORUs are expected to have been installed after the fifth year of the assembly sequence (i.e., Flight 25 in 1999).

This distribution of SSF external ORUs over the 29 STS flights formed the basis of the ORU build-up model in the failure-rate-versus-time simulation.

Table 5.4
ASSEMBLY SEQUENCE
OVERALL MANIFEST LAUNCH SCHEDULE

DATE	FLIGHT			ASSEMBLY ELEMENTS
3/31/95	1	FEL	MB-1	STBD INBOARD INTEGRATED EQUIPMENT ASSEMBLY, 2 SOLAR ARRAY/BETA JOINT, TRUSS BAYS SA1-SA2, STBD UTILITIES SA2-SA1, ALPHA JOINT. ASSEMBLY WORK PLATFORM, ASTRONAUT POSITIONING SYSTEM, UNPRESS, DOCK ING ADAPTER, MOBILE TRANSPORTER, FTS, FTS SAE, PASSIVE DAMPERS
6/15/95	2		MB-2	TRUSS BAYS SB8-SB1, UTILITIES SB8-SB5, STBD KU ANTENNA PALLET WITH AVIONICS, 2 PROPULSION PALLETS, STBD CENTRAL TCS PALLET, CETA DEVICE, PASSIVE DAMPERS
8/30/95	3		MB-3	STBD & PORT TCS RADS AND CONDENSERS, UTILITIES SB4-SB1, PMAD PALLET, MODULE SUPPORT TRUSS, GNC PALLET, APAE SIA
11/15/95	4		MB-4	FORWARD PORT NODE, PRESS, DOCKING ADAPTER, MRS, CUPOLA
1/31/96	5		MB-5	O2/N2 REPRESS TANKS, PORT TCS PALLET, UTILITIES PB1-PB7, PROPULSION PALLET, PORT KU ANTENNA PALLET, 2 ULC BERTHING MECH, TRUSS BAYS PB1-PA6, SA3-SA6
4/1/96	6		MB-6	PORT INBOARD INTEGRATED EQUIPMENT ASSEMBLY, 2 SOLAR ARRAY/BETA JOINTS, UTILITIES PA1-PA6, SA3-SA6, ALPHA JOINT, MT BATTERIES, PROPULSIONS PALLET
6/15/96	7	MTC	MB-7	U.S. LAB MODULE CORE, 6 SYSTEM RACKS, 1 USER RACK

Table 5.4 (Continued)

DATE	FLIGHT			ASSEMBLY ELEMENTS
8/30/96	8		OF-1	PRESS . LOG. MODULE, 13 LAB SYSTEMS RACKS, 6 USER RACKS, SPDN, MMD
11/15/96	9		MB-8	AFT PORT NODE, AFT STBD NODE, NODE UMBILI-CALS
1/31/97	10		MB-9	HAB MODULE CORE, 18 SYSTEM RACKS
4/1/97	11		OF-2	PRESSURIZED LOGISTIC MODULE, 17 HAB SYS-TEM RACKS, O2-N2 REPRESS TANKS
6/15/97	12		MB-10	FORWARD STBD NODE, AIRLOCK, EMUs, CUPOLA
7/30/97	13	PMC	L-1	CREW, PRESSURIZED LOGISTICS MODULE, UNPRESSURIZED LOGISTICS CARRIER, CRYO O2 SUBCARRIER, CRYO N2 SUBCARRIER, DRY CARGO SUBCARRIER, LOGISTICS RESUPPLY
9/15/97	14		MB-11	STBD OTBD IEA, 2 SOLAR ARRAY/BETA JOINTS, PORT OTBD IEA, 2 SOLAR ARRAY/BETA JOINTS
10/31/97	15		L-2	PRESSURIZED LOGISTICS MODULE, LOGISTICS RESUPPLY
12/15/97	16		L-3	2 HYDRAZINE RESUPPLY TANKS, UNPRESS. LOGISTICS CARRIER, CRYO O2 SUBCARRIER, CRYO N2 SUBCARRIER, DRY CARGO SUBCAR-RIER, LOGISTICS RESUPPLY
2/1/98	17		MB-12	JEM MODULE, JEM PDCU'S AND HEAT EX-CHANGER
3/15/98	18		L-4	PRESSURIZED LOGISTICS MODULE, LOGISTICS RESUPPLY
4/30/98	19		L-5	2 HYDRAZINE RESUPPLY TANKS (#11, 12) UN-PRESS. LOGISTICS CARRIER, CRYO O2 SUBCAR-RIER, CRYO N2 SUBCARRIER, DRY CARGO SUB-CARRIER, LOGISTICS RESUPPLY

Table 5.4 (Continued)

DATE	FLIGHT		ASSEMBLY ELEMENTS
6/15/98	20	MB-13	ESA MODULE, ESA PDCUs & HEAT EXCHANGER
7/30/98	21	L-6	PRESSURIZED LOGISTICS MODULE LOGISTICS RESUPPLY, ECLSS UPGRADE
9/15/98	22	MB-14	JEM EXPOSED FACILITY 1 & 2, JEM ELM PS, JEM ELM ES
10/31/98	23	L-7	2 HYDRAZINE RESUPPLY TANKS, UNPRESS. LOGISTICS CARRIER, CRYO O2 SUBCARRIER, CRYO N2 SUBCARRIER, DRY CARGO SUBCARRIER, LOGISTICS RESUPPLY
12/15/98	24	L-8	PRESSURIZED LOGISTICS MODULE, LOGISTICS RESUPPLY
1/31/99	25	OF-3	PRESS. LOG. MODULE, NODE & MODULE OUTFITTING, FMAD, STINGER RESISTOJET, MT/MSC UPGRADES, APAE SIA ALPHA JOINT UPGRADES APAE POWER UPGRADE
3/15/99	26	L-9	2 HYDRAZINE RESUPPLY TANKS, UNPRESS. LOGISTICS CARRIER, CRYO O2 SUBCARRIER, CRYO N2 SUBCARRIER, DRY CARGO SUBCARRIER, LOGISTICS RESUPPLY
4/30/99	27	L-10	PRESSURIZED LOGISTICS MODULE, LOGISTICS RESUPPLY
6/15/99	28	OF-4	PRESS. LOG. MOD, MOD OUTFITTING & DMS/MS UPGRADES, C&T UPGRADES PRESS. DOCKING ADAPTER, CMG UPGRADES, PMAD UPGRADES, BERTH MERCH UPGRADES, CREW OF 8
7/30/99	29	L-11	2 HYDRAZINE RESUPPLY TANKS, UNPRESS. LOGISTICS CARRIER, CRYO O2 SUBCARRIER, CRYO N2 SUBCARRIER, DRY CARGO SUBCARRIER, LOGISTICS RESUPPLY

ORU'S BY FLIGHT

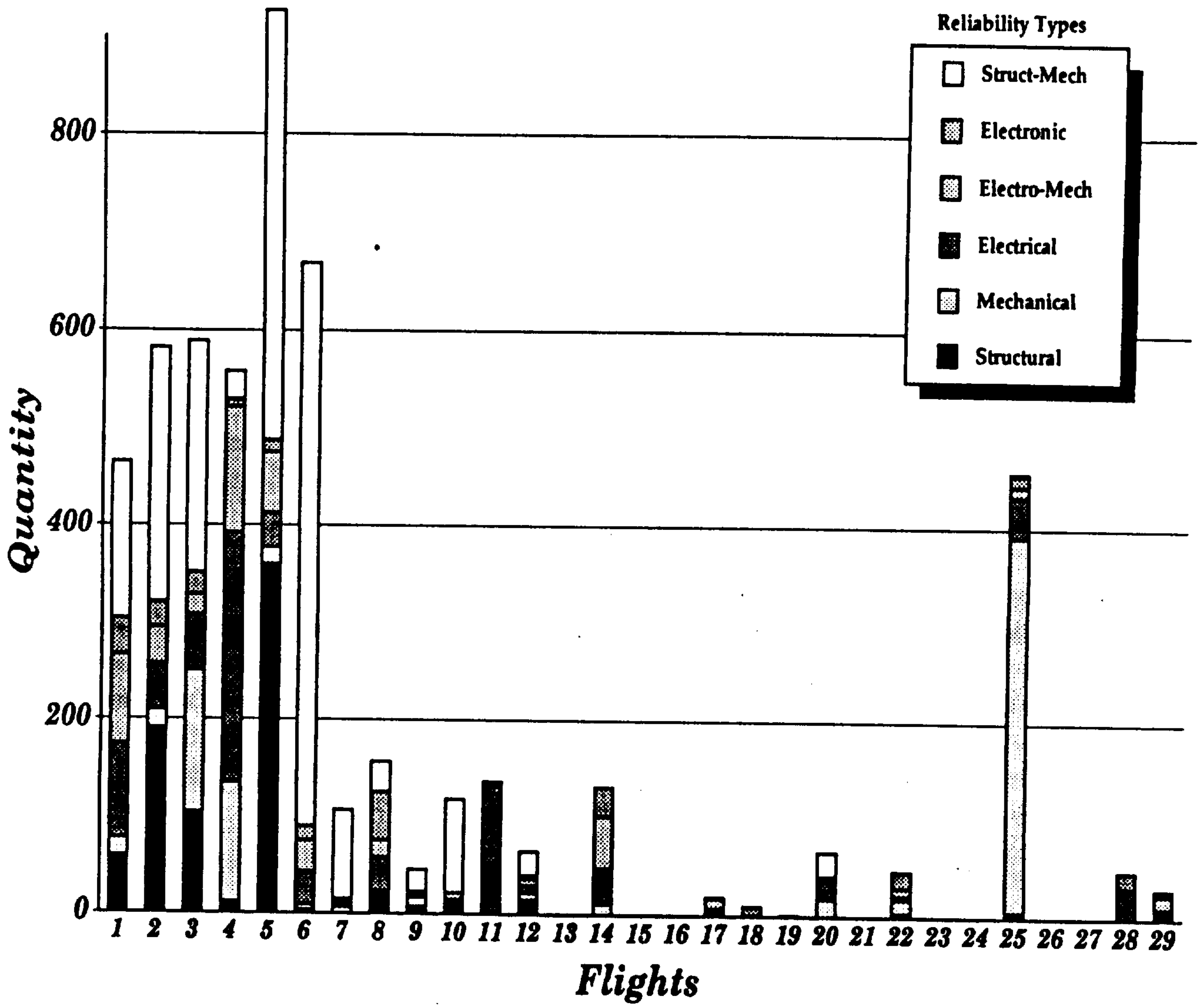

Figure 5.5

5.7. Modeling of ORU Failures Over Station Lifetime.

There are four major effects on the occurrence of failures over the lifetime of the SSF:

- Random ORU failures
- Initialization failures
- Life limit failures
- SSF construction schedule

The summation of all effects cannot easily be described by a solvable equation, and, at the writing of this report, each effect has a random component to it. Therefore, a Monte Carlo simulation of the life of the space station was performed. The simulation is described in the following subsections.

5.7.1. Random Failures.

The simplest approach in terms of data requirements and computational ease is to simply generate times to failure for each ORU using an exponential distribution and a calendar-based failure rate, and assign the EVA to the appropriate month. This approach does not take into account repairs and non-repairs, nor does it give a straight forward way to model cycled ORUs. However, the calculation of failure rate using the method described in Section 5.5. factors in the duty cycle. The underlying assumption in this model is instantaneous repair with no change in the failure probability. The equation is derived from the cumulative distribution function for failure times which is:

$$P(T \leq t) = 1 - e^{-\lambda t} = r$$

where r is a uniformly distributed random number between 0 and 1.

The equation can be solved to the following equation for time of failure:

$$t = \frac{\ln(1-r)}{-\lambda}$$

Our simulation generated a time to next failure, and assigned that failure to the approprate month. A second time to failure was randomly generated, and added to the time to the first failure to give the time of the second failure. This process continued until a failure time exceeded the life of the Space Station, at which time the simulation was complete for this ORU.

5.7.2. Initialization Failures.

As discussed in section 5.6, "early failure effects" are expected to cause a decline in the overall random failure rate from an uncharacteristically high level early in the life of the Station to a lower, relatively stable level.

Precise prediction of initialization failure rates is generally more difficult than predicting steady- state failure rates. Rather than choosing a theoretical "infant mortality model" to predict this phenomena, we choose a data oriented approach, using the data from an RADC study of satellites discussed in section 5.6.4 and illustrated by Figure 5.3.

5.7.3 Modeling of Life-Limit Failures.

Section 5.4 discusses the life limited ORUs and their failures in some detail. For the purposes of simulation, the variation of the time around the life limit is random and described by a triangular distribution with a total width of 12 months for ORUs with a life limit of less than or equal to 10 years and of 24 months for those with life limits of greater than 10 years.

5.7.4 Modeling of the Construction Schedule.

Table 5.4 shows the construction schedule used for the simulation.

5.7.5. Simulation Description and Results.

The simulation runs through the entire logic for each of the 8158 ORUs and records the failure information for plotting. The basic logic of the simulation, in the sequence performed by the computer code is:

1. Start date. (Section 5.7.4): Randomly determine which shuttle flight delivered the ORU from the distribution drawn in Figure 5.5.

2. Initialization period (Section 5.7.3): For each month of the initialization period calculate a failure rate from the data base and the initialazation factor. Draw a random number to determine if a failure occurs in that month, and if a failure occurs, the failure count for that month is increased by one.

3. Constant Failure Rate Period (Section 5.7.1): Determine the times of failures out to the end of the simulation.

4. Life-limits (Section 5.7.3): The life-limit event times are calculated from the start date. Give credit for good-as-new ORU replacement at the time of initialization or random failure. Determine the life length randomly.

SAIC used the simulation model to create Figures 5.6 through 5.9,a series of bar graphs showing projected profiles of failures versus time. These simulation results are discussed in the following paragraphs. Note that projected ORU failures are subdivided according to ORU technology classification (electronic, mechanical, etc.) where scale considerations permitted.

Figure 5.6 covers the first four years following "First Element Launch," and illustrates the combined expected effects of gradual ORU build-up during construction, initialization failures, and the onset of reliability growth. To highlight these effects, life-limit replacements were excluded from the simulation model for this case. Note that the relatively slow accretion of ORUs tends to compensate for initialization by spreading early ORU failures over several years.

Of course, the failures will still occur, but many of them will be delayed because the affected ORUs will not arrive until late in the construction phase. This delay is probably a net disadvantage for two reasons: (1) Unless maintenance resources are available during construction, Freedom will accumulate a substantial backlog of unrepaired failures before the permanent crew arrives, which will have to be worked off while new failures are continually occurring. (2) The early failures of late-arriving ORUs will tend to occur after the Shuttle-borne construction crews have been replaced by a smaller and presumably less EVA-adept permanent staff.

In Figure 5.7 we show the results of the Monte Carlo simulation in terms of ORU failures per year over 35 years (the 30-year design life plus 5 years to allow for the possibility of some life extension). This simulation run incorporated all four terms of the external ORU failure model, including ORU build-up, initialization, reliability growth, and life-limits. The graph clearly shows the peaks in external maintenance effort caused by coincident 5-, 10-, and 15-year life-limit replacements. Also note the peak in Year 2, caused by a combination of initialization failures, random failures, and 2-year end-of-life replacements.

Figure 5.8 also shows 35 years of projected failures, but on a monthly basis. It illustrates both the life-limit peaks and the significant month-to-month variations due to the random incidence of non-life-limit failures.

In Figure 5.9 the month-by-month Monte Carlo simulation results are divided into 3-year segments spread over several pages for legibility.

The particular run, or snap shot simulation of the data, shown in this section yielded an average of 181 failures per year over the 35 year life cycle modeled. Of this 181 failures, 107 per year were random failure events and 74 were life limit events. Since the model is based on a random simulation, a large number of computer runs would be required to establish an exact mean. However, since a large number of ORUs are modeled for 35 years, the mean annual failures should not vary significantly . To verify this, we performed several additional runs and confirmed that all came within 5 failures per year of the 181 figure.

The total number of failures calculated from the simulation vary somewhat from these calculated using the methods described in Section 5.5. The tabulation method of section 5.5 yielded 231 failures per year, made up of 149 random failures per year and 82 life limit failures per year. The difference, mainly in the random failure estimate, is caused by two phenomena:

- The average taken from the simulation includes early years with relatively few ORUs in space while the tabulation assumes all ORUs operating from exactly the start of year number 1 to the end of year number 30.

- The steady state failure rate used by the simulation is estimated to be two thirds of that used in the tabulation. This effect is offset somewhat, but not completely by the calculation of initialization effects.

Neither the difference of the two average estimates nor the correctness of one estimate relative to the other should be regarded as a major issue. The two methods represent different ways of modeling real phenomena with reliability data, and the results are substantially the same subject to varying assumptions. The simulation does a better job at showing the variations over the years and the interrelationship between random failures and life limit failures, but the averaging across 35 years is not directly comparable to the tabulation. The tabulation provides a firm basis for comparison and averaging, but does not model the construction schedule, changing failure rates or interrelationships.

Effects Of Initialization On Early Failure Events

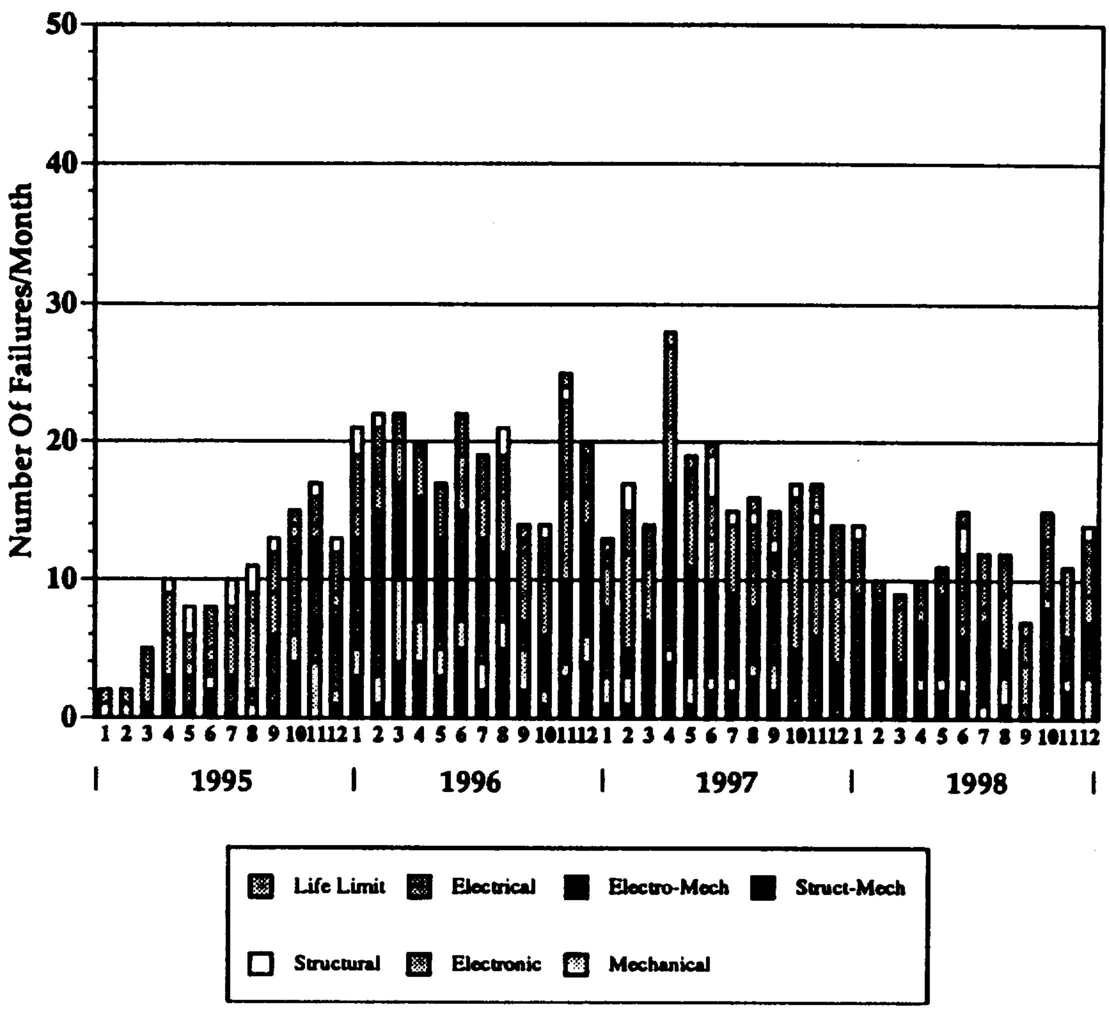

Figure 5.6

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ORU Failures by Year

Generated by Monte Carlo Simulation

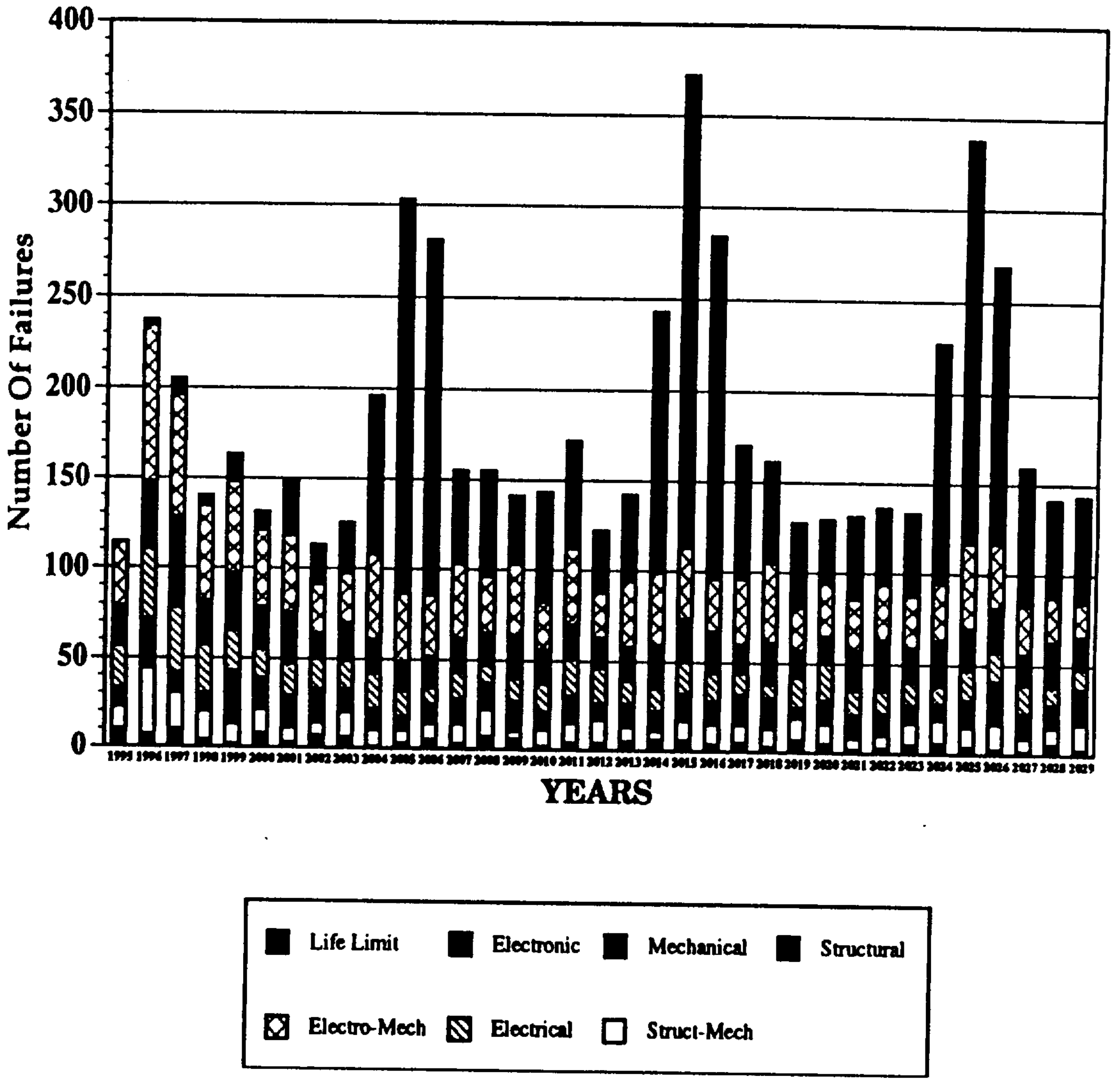

Figure 5.7

EMTT

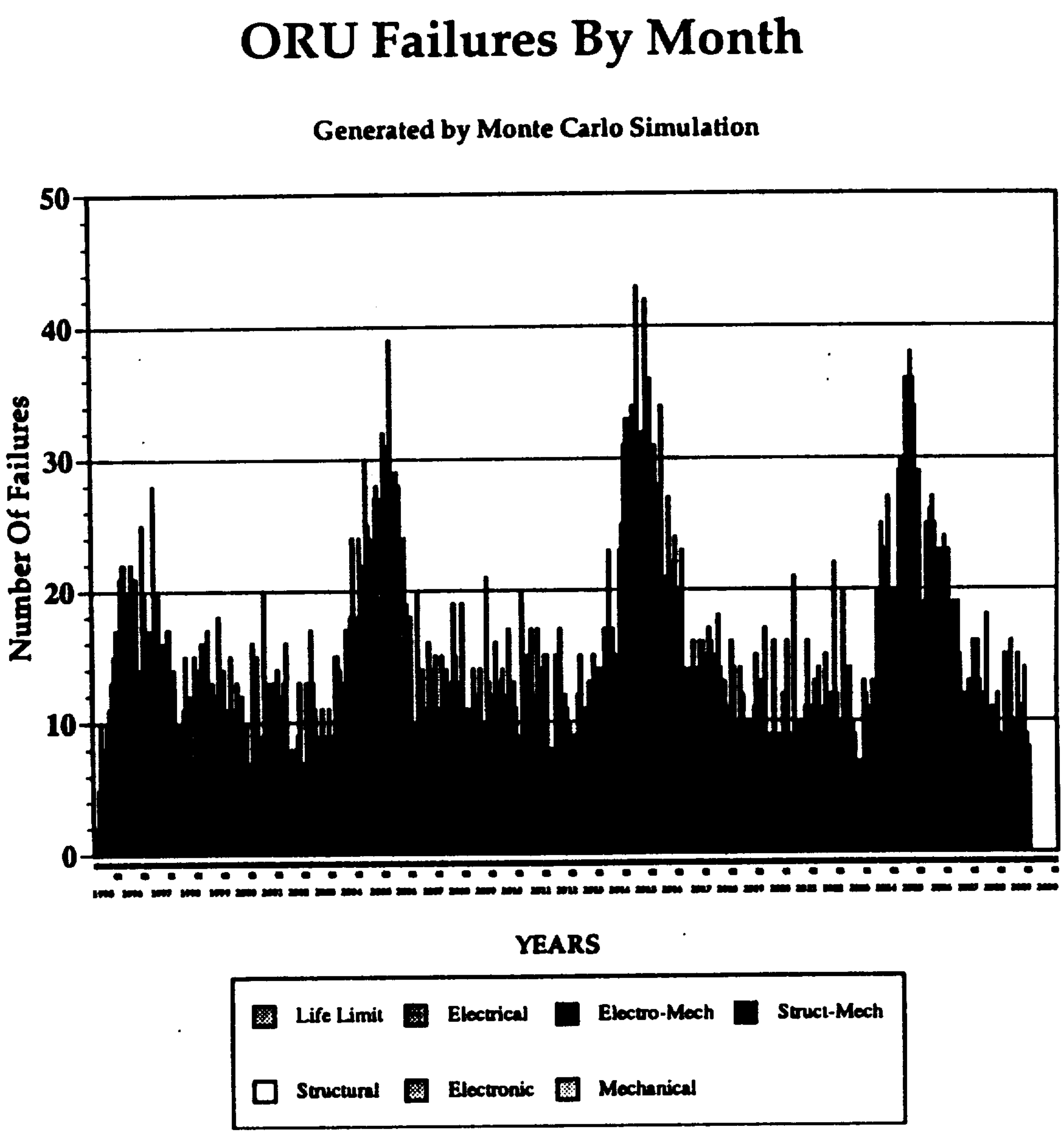

Figure 5.8

EMTT

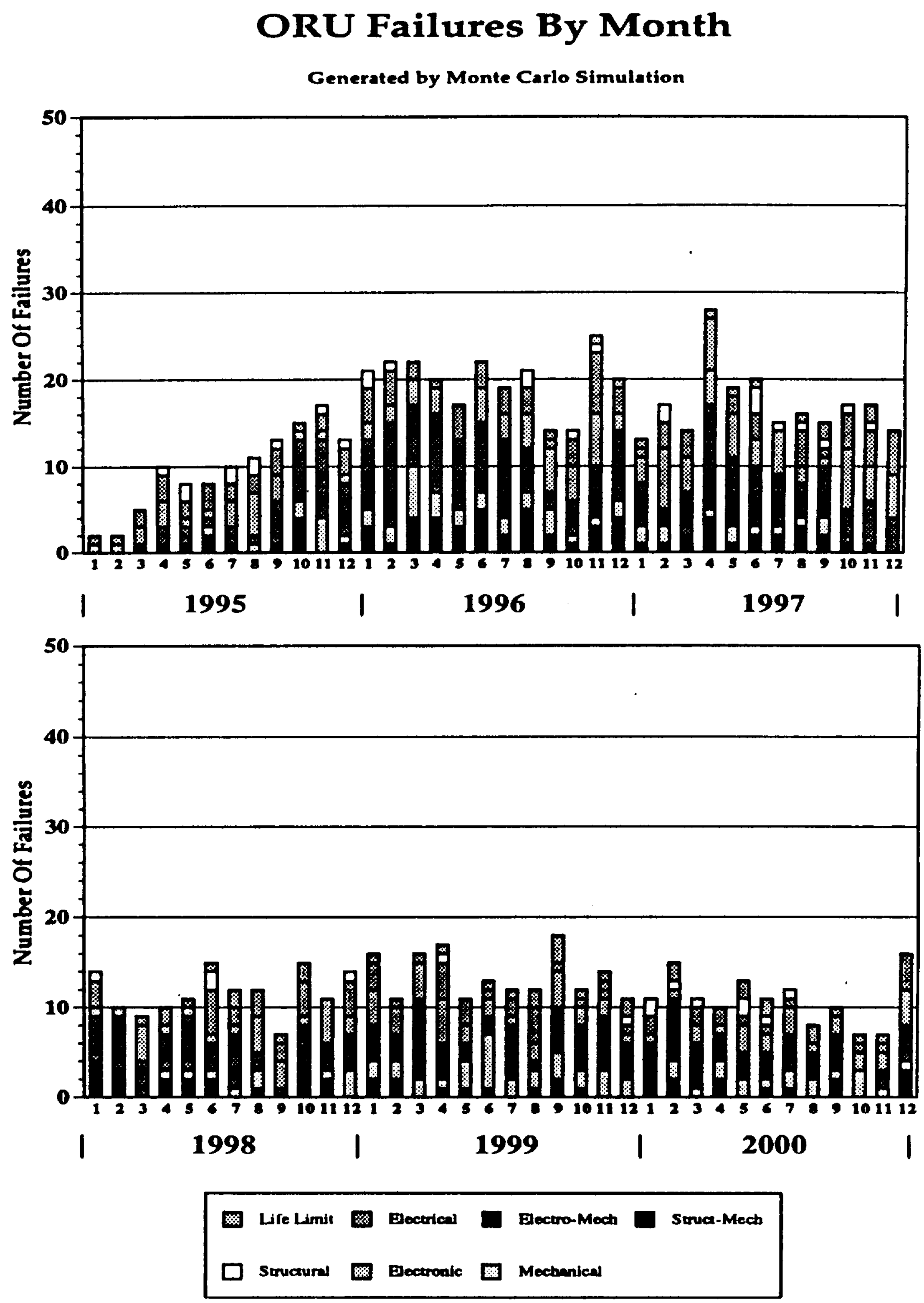

Figure 5.9.1

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ORU Failures By Month

Generated by Monte Carlo Simulation

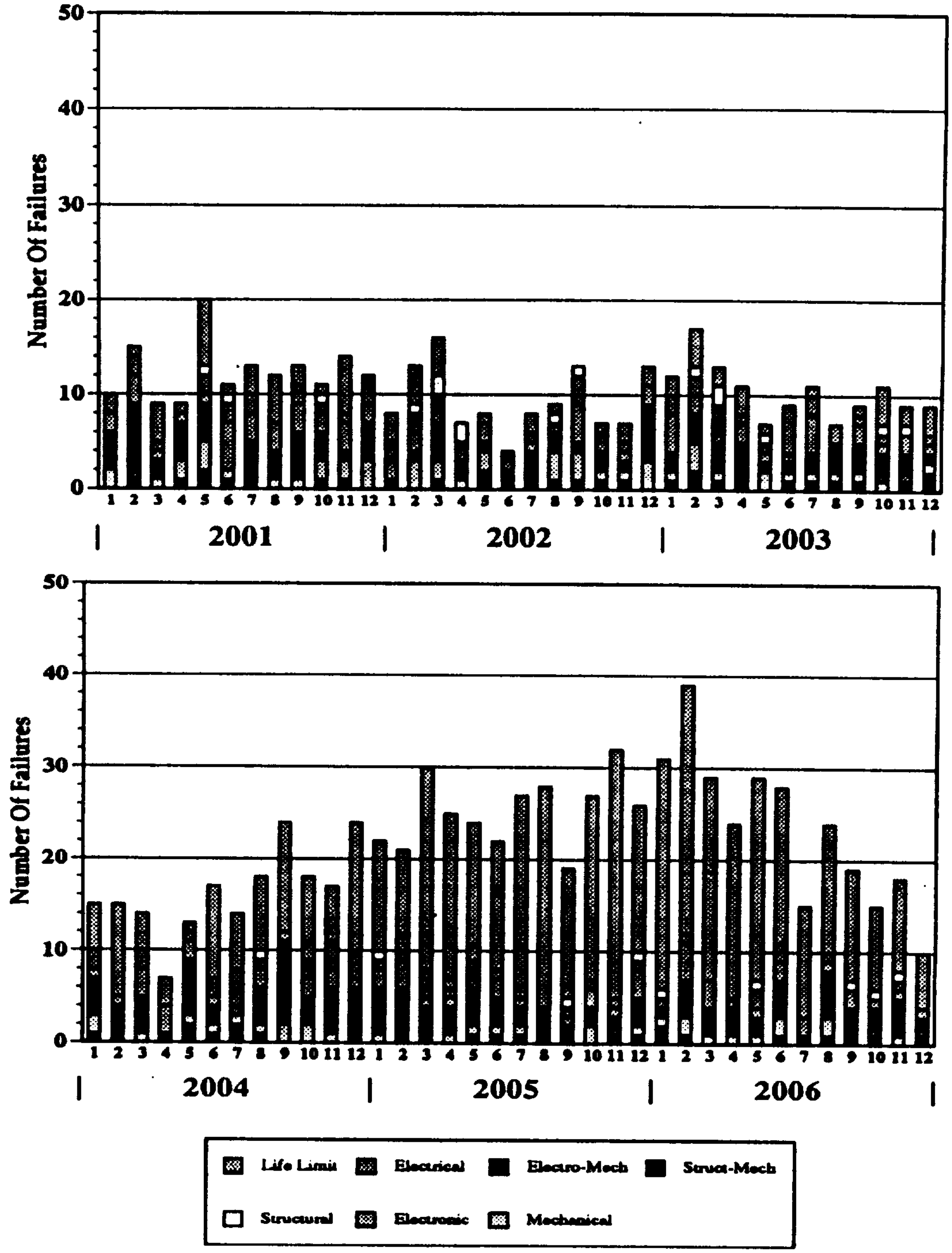

Figure 5.9.2

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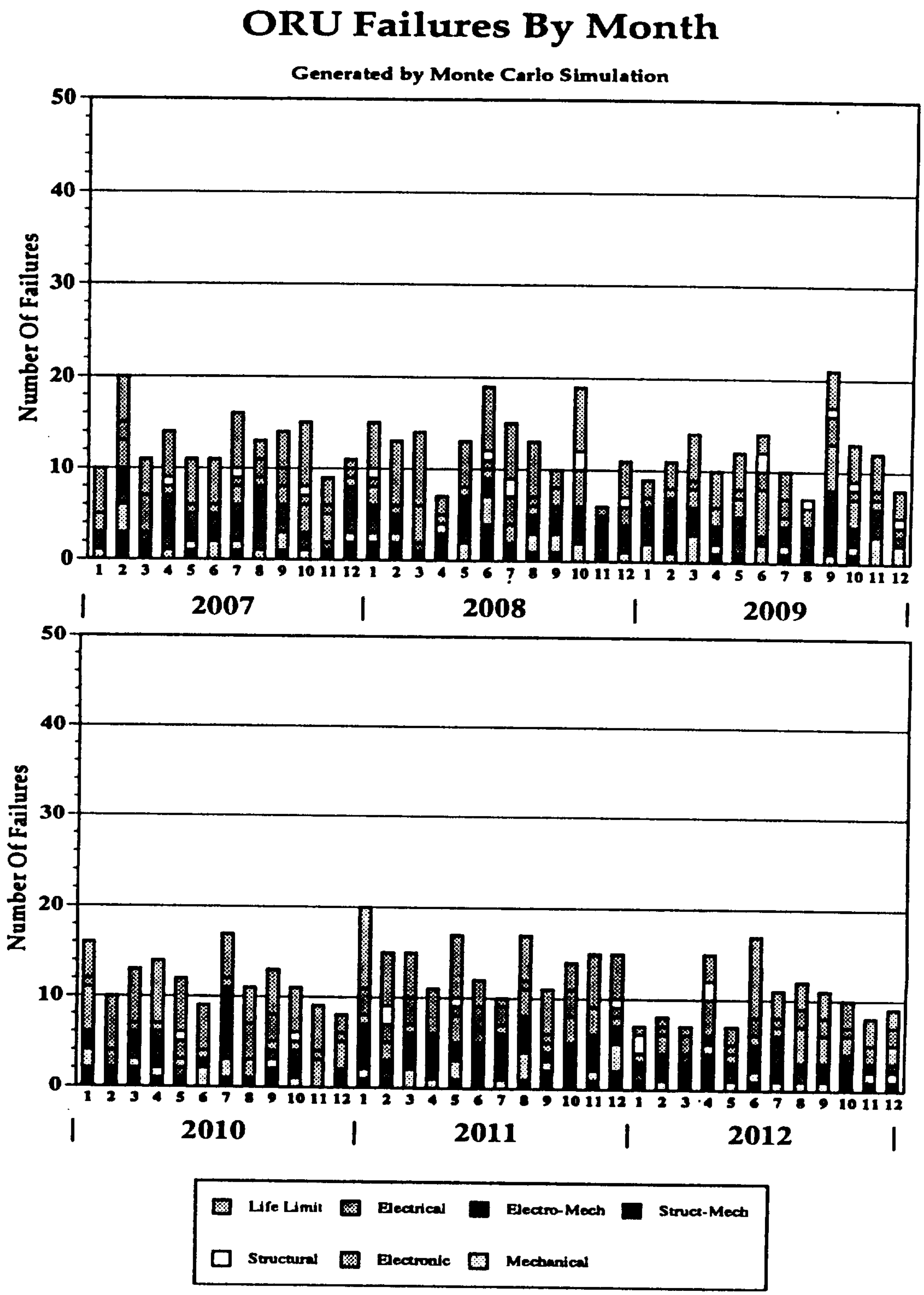

Figure 5.9.3

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ORU Failures By Month

Generated by Monte Carlo Simulation

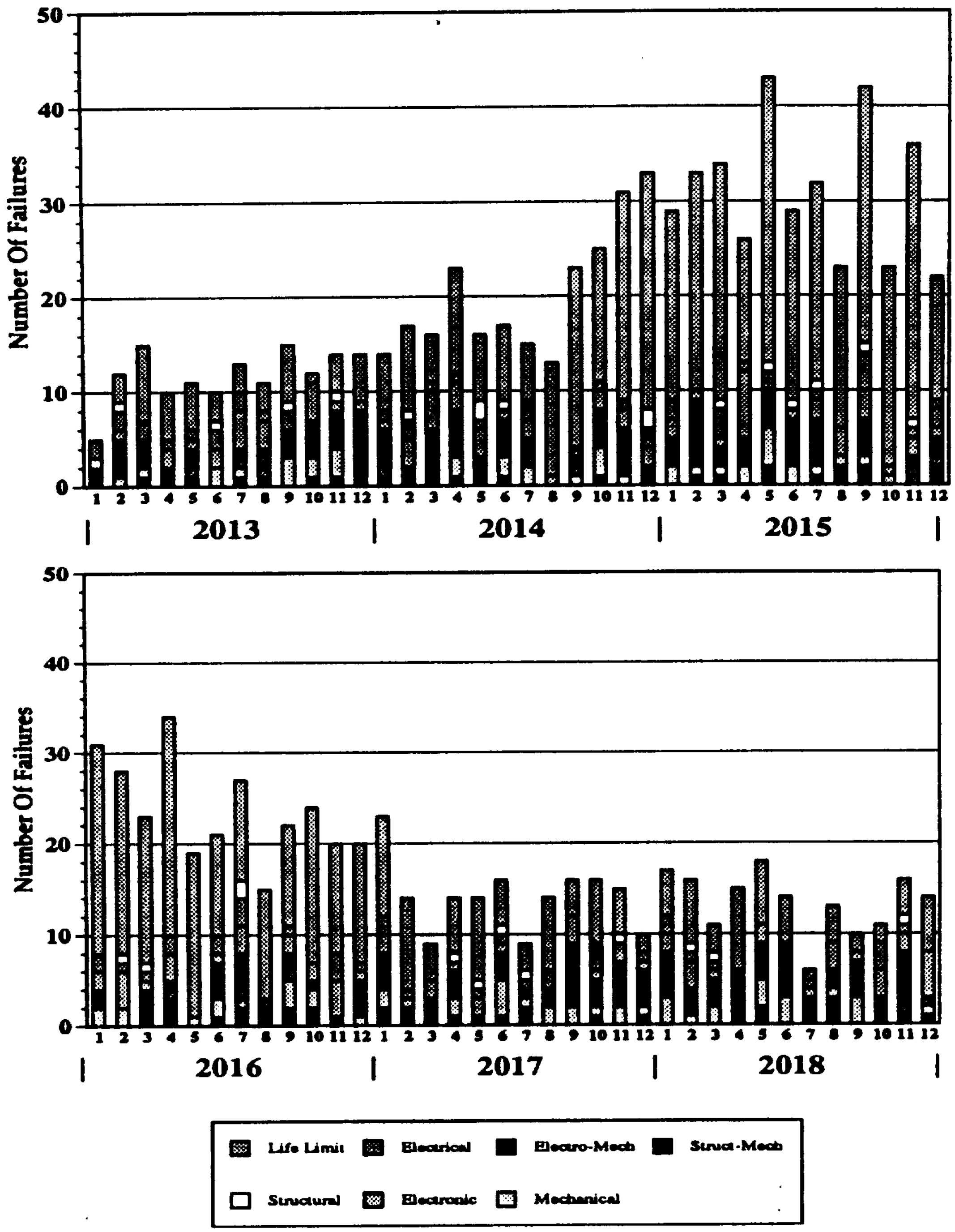

Figure 5.9.4

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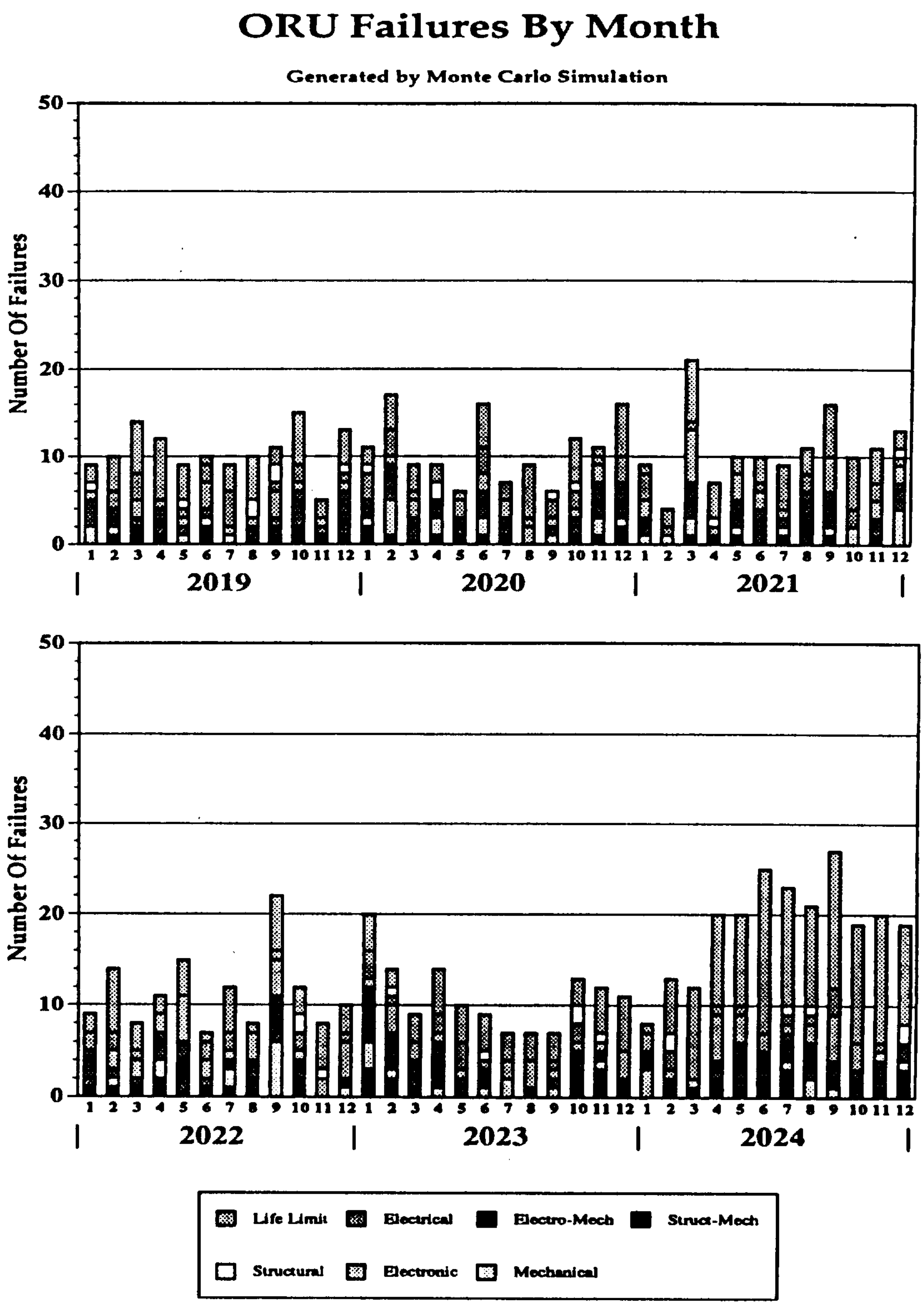

Figure 5.9.5

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ORU Failures By Month

Generated by Monte Carlo Simulation

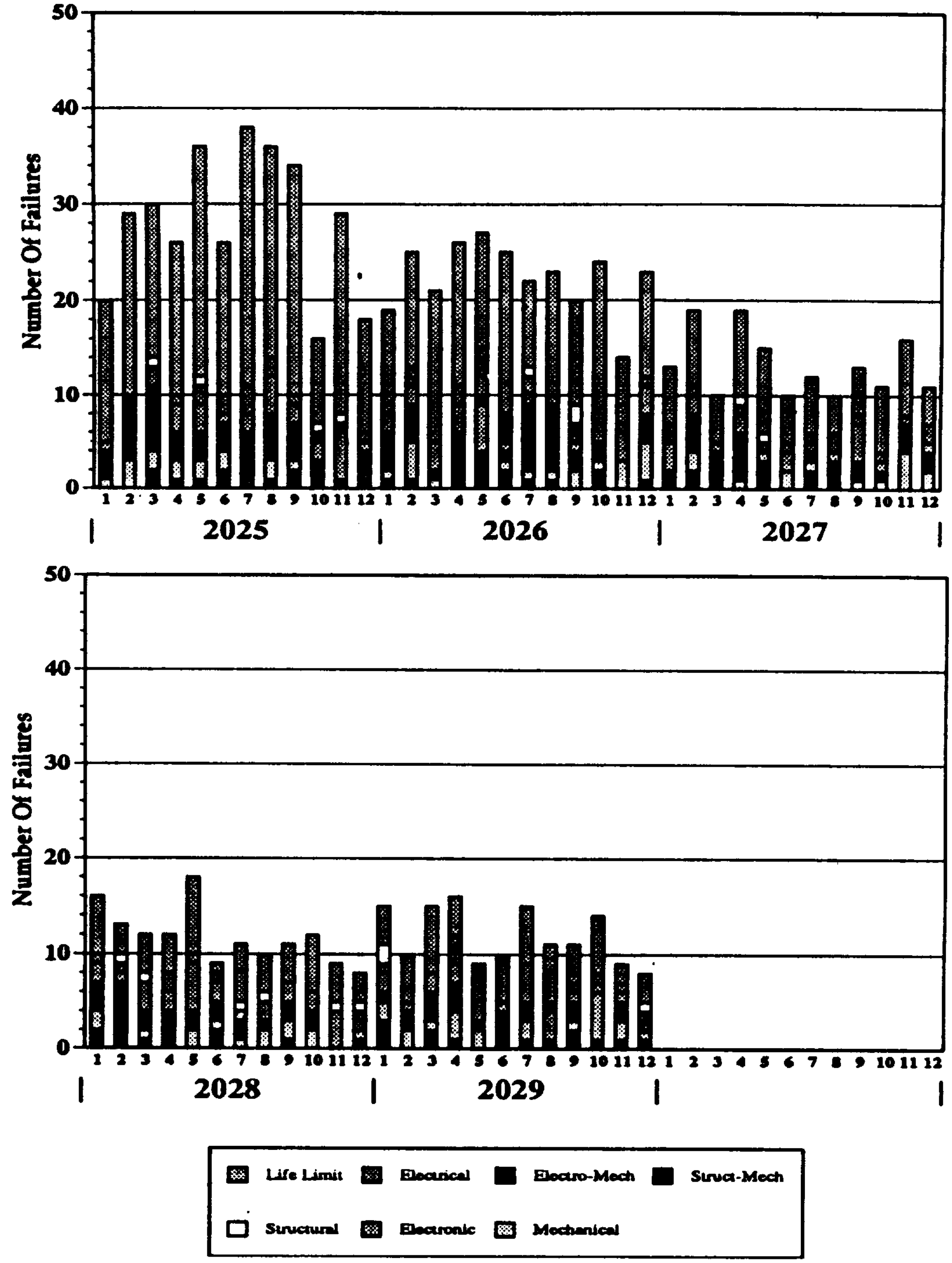

Figure 5.9.6

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6.0. SUMMARY AND COMPARISON OF THE RESULTS OF THE ANALYSIS.

6.1. Review of the Analysis.

As discussed previously in this report, SAIC considered life-limit effects separately from random failures in the Space Station *Freedom* Reliability Data Analysis. The SAIC data analysis team was not technically qualified to second-guess the Work Package and International Partner (WP/IP) engineers on design life, a fundamental design issue. Consequently we used the WP/IP life-limit information without changes in the failures-versus-time simulation and the ranking of external ORUs by their contribution to total maintenance EVA. We concentrated most of our analytical effort on random external ORU failure rates.

We used a three-phased approach to assess the WP/IP random failure data and create an independent, validated ORU reliability data base for use in projecting external EVA requirements. The primary technique was a detailed review and audit of the sources and methodology underlying the WP/IP reliability analyses. We also provided a "sanity check" on the WP/IP random ORU failure rates by developing two sets of typical Space Station ORU random failure rates by two processes which were completely independent of the WP/IP reliability analyses and also of each other. One was the "generic ORU synthesis" approach, in which three reliability experts postulated typical ORUs and developed failure rates for them based on engineering judgement and generic component reliability data. In the second, "in-service" approach, we extracted random failure rates for typical Space Station ORUs from an analysis of the historical experience of operational spacecraft.

The following sections summarize and compare the results and conclusions of the Reliability Data Analysis. Some recommendations derived from this study and SAIC's experience are presented for NASA's consideration in section 7.0.

6.2. Summary and Conclusions for Random Failures.

Figures 6.1 and 6.2 graphically show the results of the analysis of WP/IP data compared to those of the generic ORU synthesis and in-service analyses. In Figure 6.1, non-structural ORU failure rates developed from synthesis and WP/IP data are further broken down by predominant technology (electrical, mechanical, etc.) according to the EMTT classification scheme. Table 6.1 summarizes the parameters — mean, median, and 5th- and 95th-percentile confidence bounds — of the random failure rate distributions developed by the three methods. Figure 6.3 shows how the combined rates for the in-serivce and synthesis analyses were developed.

In-Service and Work Package Approach Comparison

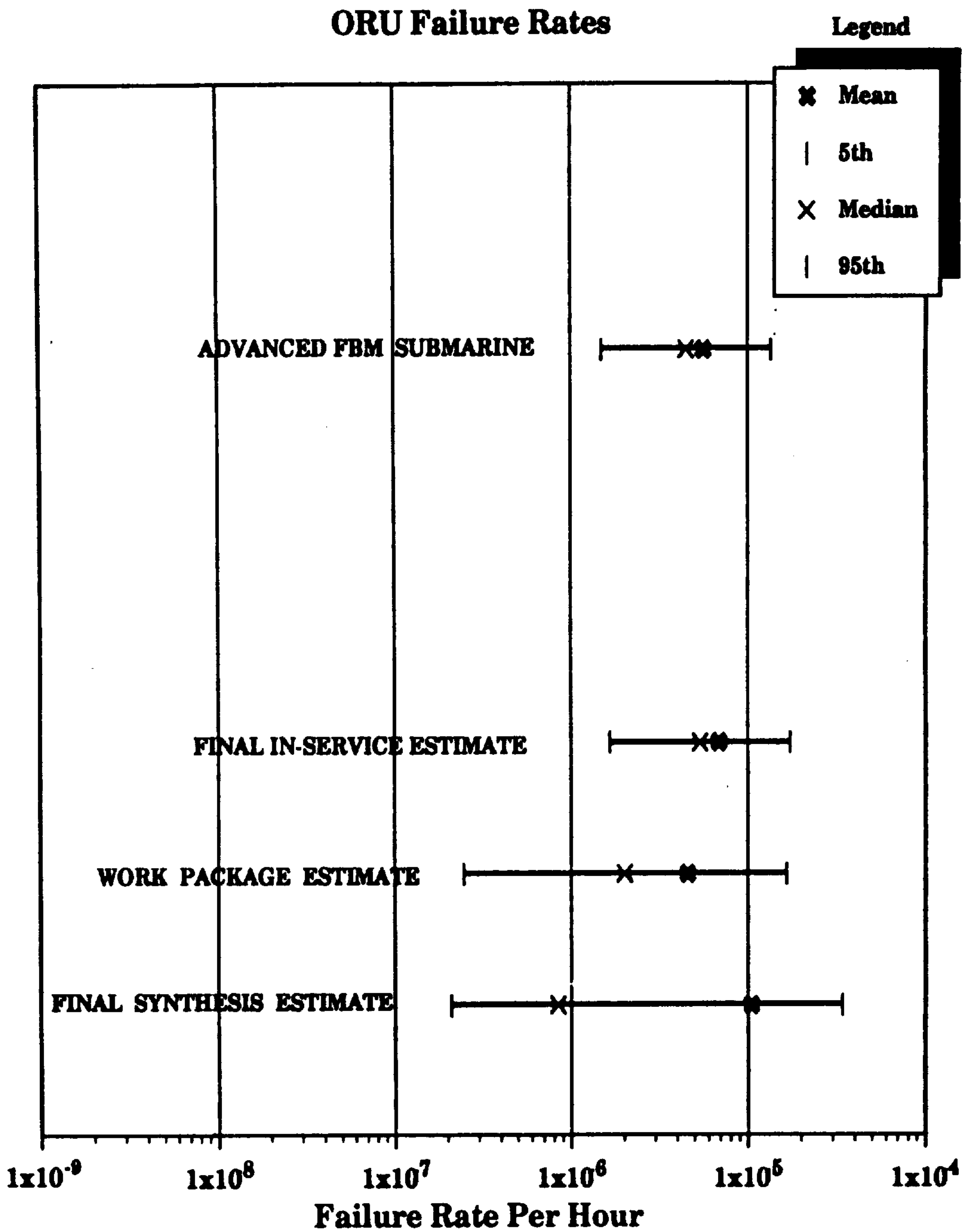

Figure 6.1

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Synthesis and Work Package Approach Comparison

ORU FAILURE RATES

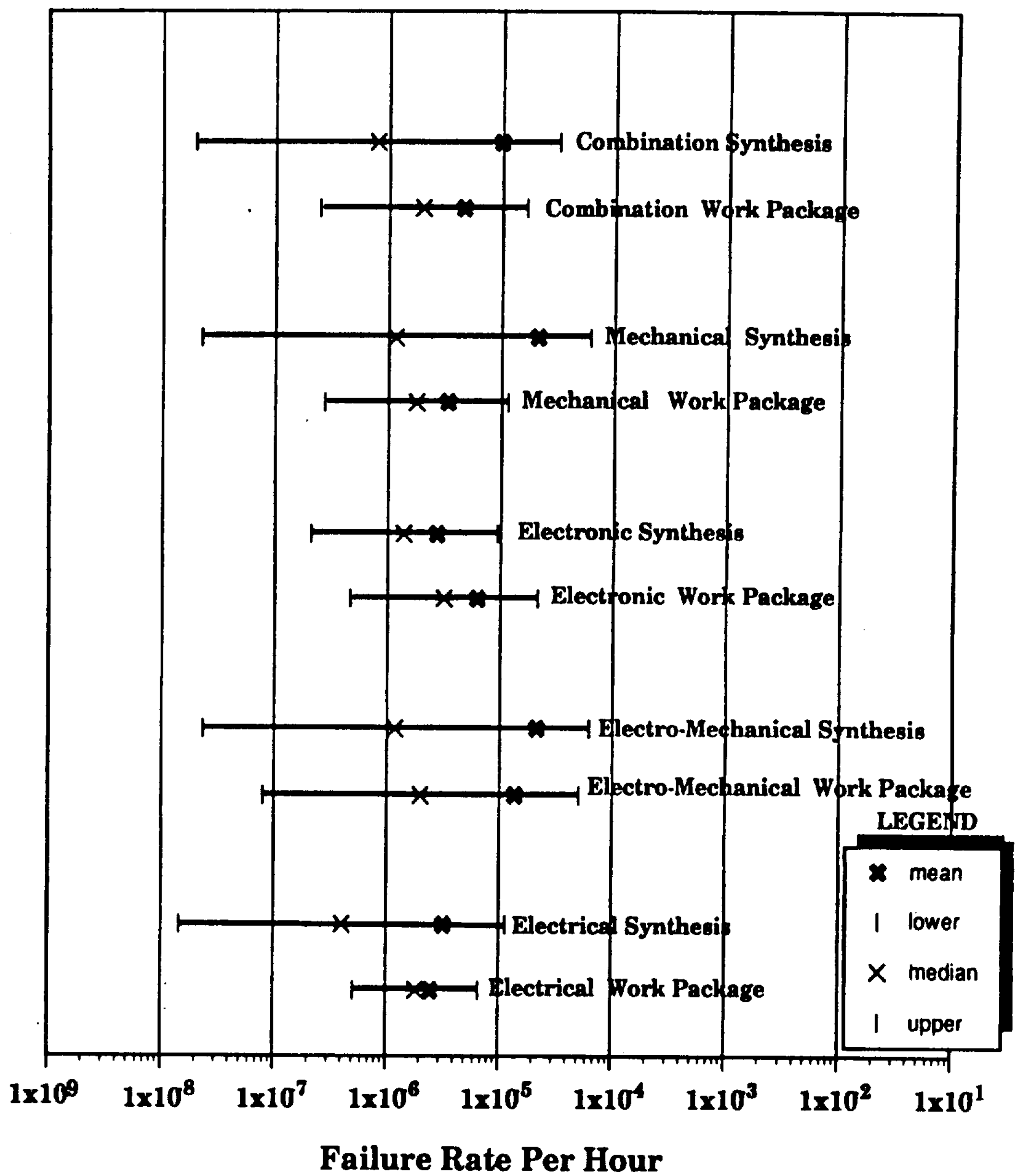

Figure 6.2

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Table 6.1 Summary of ORU Random Failure Rate Estimates From the Three Estimating Approaches

ESTIMATE	MEAN	LOWER(5th)	MEDIAN(50th)	UPPER(95th)
ELECTRICAL WORK PACKAGE	2.49×10^{-6}	5.10×10^{-7}	1.84×10^{-6}	6.62×10^{-6}
ELECTRO-MECH WORK PACKAGE	1.38×10^{-5}	7.93×10^{-8}	2.01×10^{-6}	5.07×10^{-5}
ELECTRONIC WORK PACKAGE	6.27×10^{-6}	4.70×10^{-7}	3.19×10^{-6}	2.16×10^{-5}
MECHANICAL WORK PACKAGE	3.36×10^{-6}	2.75×10^{-7}	1.77×10^{-6}	1.14×10^{-5}
COMBINATION WORK PACKAGE	4.57×10^{-6}	2.45×10^{-7}	2.01×10^{-6}	1.65×10^{-5}
ELECTRICAL SYNTHESIS	3.20×10^{-6}	1.45×10^{-8}	4.08×10^{-7}	1.15×10^{-5}
ELECTRO-MECH SYNTHESIS	2.12×10^{-5}	2.31×10^{-8}	1.19×10^{-6}	6.17×10^{-5}
ELECTRONIC SYNTHESIS	2.73×10^{-6}	2.06×10^{-7}	1.39×10^{-6}	9.40×10^{-6}
MECHANICAL SYNTHESIS	2.10×10^{-5}	2.22×10^{-8}	1.16×10^{-6}	6.09×10^{-5}
ELECTRICAL HUBBLE	5.43×10^{-6}	2.10×10^{-7}	2.07×10^{-6}	2.03×10^{-5}
ELECTRO-MECH HUBBLE	5.57×10^{-6}	1.72×10^{-8}	5.74×10^{-7}	1.91×10^{-5}
ELECTRONIC HUBBLE	3.77×10^{-6}	1.90×10^{-7}	1.62×10^{-6}	1.37×10^{-5}
MECHANICAL HUBBLE	3.87×10^{-7}	6.72×10^{-9}	1.00×10^{-7}	1.50×10^{-6}
COMBINATION HUBBLE	4.60×10^{-6}	2.70×10^{-7}	2.11×10^{-6}	1.65×10^{-5}
COMBINATION IN-SERVICE	6.90×10^{-6}	1.67×10^{-6}	5.35×10^{-6}	1.73×10^{-5}
COMBINATION SYNTHESIS WITHOUT HUBBLE	1.06×10^{-5}	2.09×10^{-7}	8.42×10^{-7}	3.41×10^{-5}
COMBINATION SYNTHESIS WITH HUBBLE	9.87×10^{-6}	1.95×10^{-8}	7.87×10^{-7}	3.18×10^{-5}
ADVANCED FBM SUBMARINE	5.63×10^{-6}	1.50×10^{-6}	4.50×10^{-6}	1.35×10^{-5}

Development Of Combined Failure Rates For Table 6.1

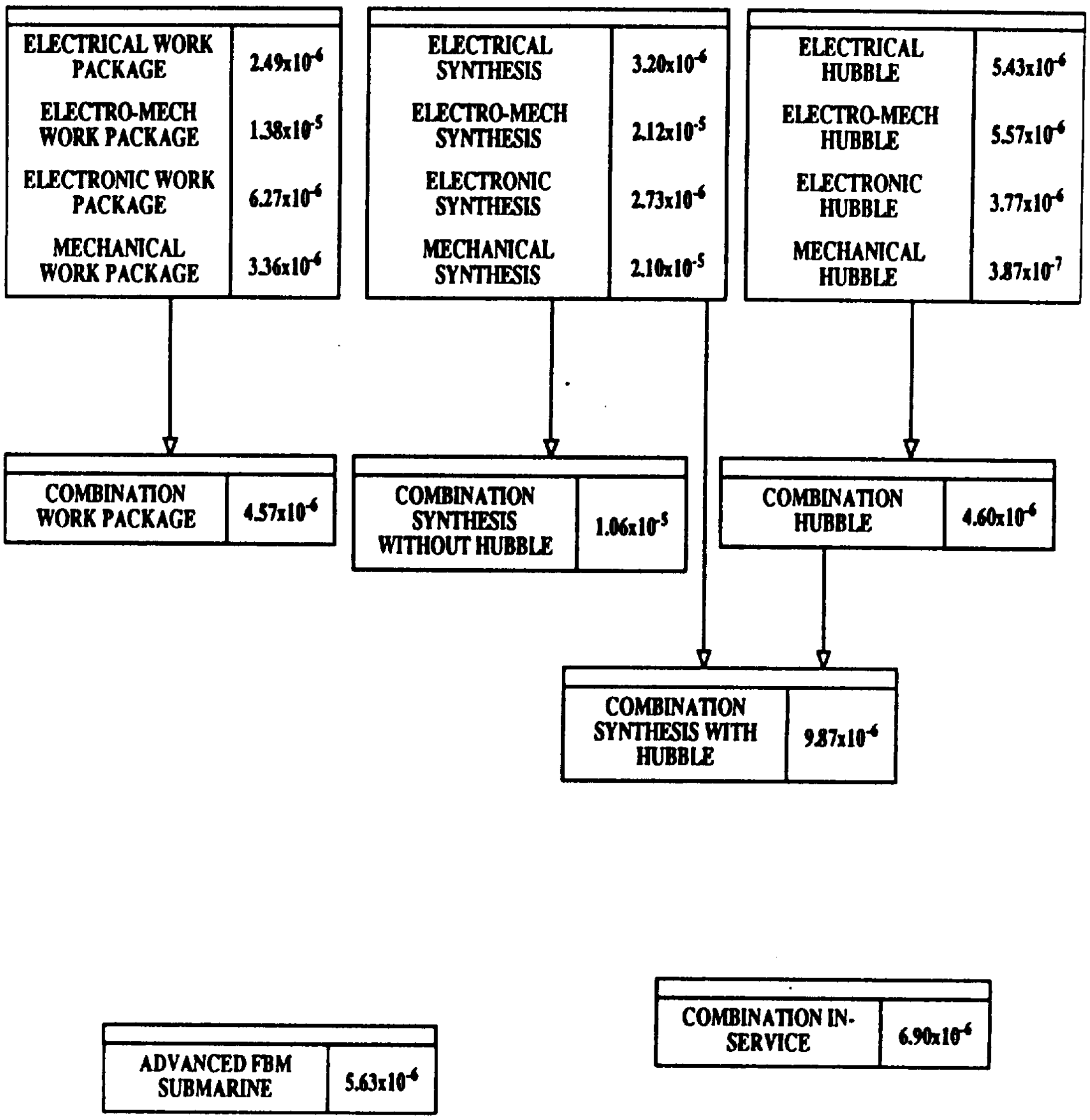

Figure 6.3

Our evaluation of the results of the random-failure element of the Reliability Data Analysis can be summarized as follows:

- On the Space Station level, the WP/IP failure rate data and the data developed by the two independent estimation processes are mutually highly consistent.

- There are differences among the synthesis and WP/IP estimates for major ORU classes in some cases, but even at this level the results are consistent within the bounds generally considered acceptable for reliability predictions for equipment which is still in preliminary design.

- The consistencies among the random failure estimates justify a high level of confidence in the validity of the analysis and its conclusions.

6.3. Projected Failures Over the Life of the Space Station.

There are two aspects to this topic: the profile of failures versus time, and the ranking of major contributors to maintenance EVA. We will discuss them separately.

6.3.1. Failures Versus Time Over the Life of the Space Station.

SAIC projected the monthly and annual rate of external ORU failures over the life of Space Station *Freedom* using a Monte Carlo simulation model which was based on audited WP/IP data, and incorporated the effects of random failures, initialization and reliability growth, gradual build-up of ORUs during construction, and ORU life-limits. The key results of this projection are the following:

- Initialization failures and the countervailing effect of reliability growth dominate maintenance EVA requirements during the early years of the Space Station.

- The delayed arrival of many ORUs during construction correspondingly delays the impact of early-failure phenomena, but this delay is probably a net disadvantage for two reasons:

  - Unless maintenance resources are available during construction, *Freedom* will accumulate a substantial backlog of unrepaired failures before the permanent crew arrives, which will have to be worked off while new failures are continually occurring.

  - The early failures of late-arriving ORUs will tend to occur after the Shuttle-borne construction crews have been replaced by a smaller and presumably less EVA-adept permanent staff.

- Life-limit replacements will peak in the years which are integral factors of 30, with the largest peaks at Years 10 and 20. While replacements of life-limited ORUs at times other than end-of-life will tend to smooth the peaks somewhat, the 30-year life of the Station does not contain enough replacement cycles for this phenomenon to have a significant effect.

6.3.2. Ranking of External ORU Types by Contribution to Station Lifetime Failures.

This analysis of WP/IP offers several instructive results:

- While end-of-life replacements are a major contributor to maintenance EVA, they are not dominant. Random failures contribute 64% of the lifetime maintenance actions.

- The usual Pareto relationship applies to Space Station external maintenance, in the sense that the highest-ranked 100 ORU types (approximately the top 20%) are projected to contribute approximately 80% of the EVA maintenance actions over the life of *Freedom*.

- However, even if the top 20% of ORU types could be made entirely failure-proof — which of course is impossible without eliminating them from the Station — the remaining 20% of the original maintenance EVAs would still exceed the one- EVA-per-month goal.

6.4. Conclusions.

In summary, the principal conclusions of the Space Station Reliability Data Analysis are the following:

- Both direct, detailed assessments and comparisons with independently derived estimates demonstrate that with a few inconsequential exceptions the ORU reliability data furnished by the Work Packages and International Partners is credible and well supported.

- Analysis of this validated reliability data indicates that total external maintenance actions will average 231 per year or 19 per month with the baseline Station configuration and the current operation and maintenance (O&M) philosophy.

- Reduction of this burden to a target of one maintenance EVA per month would require more than a ten-fold increase in the mean time between maintenance actions of a typical external ORU, again assuming the baseline configuration and current O&M approach. The experience of the most reliable operational spacecraft, *Voyager*, demonstrates that this is beyond the potential of available or reasonably forseeable technology.

- The large number of external maintenance actions is driven primarily by the sheer number of ORUs present on the Space Station. With this large a population, the reliability of individual components becomes almost irrelevant, because no feasible improvement in component reliability will suffice to eliminate the problem. The large population in turn primarily results from three factors: (1) a design philosophy which depends exclusively on redundancy to increase reliability and maintain functionality even under multiple failures, (2) a design requirements to monitor, isolate, and replace which translates into a large number of supporting and auxiliary components, and (3) an operating and maintenance philosophy which assumes that any failure, even in an auxiliary component, must be corrected.

7.0. RECOMMENDATIONS.

The NASA EMTT has asked SAIC to offer recommendations for Space Station R-A-M improvement. The following suggestions are derived both from the Reliability Data Analysis and from our experience in R-A-M analysis and program development for aerospace, industrial, and power generation applications.

- The principal root cause of the projected high maintenance EVA demand is the number of components present. In the short term, therefore, NASA should critically re-evaluate the design itself as well as the design and O&M operation and maintenance principles which have led to it. One approach of proven effectiveness is to "zero-base" the design, i.e., to hypothesize a minimum-function configuration without redundancy and without auxiliary monitoring, isolation, and protection components, and then to restore only those components which are essential to safety or mission security.

- The key long-term recommendation of both the SAIC project team and the independent Blue Ribbon Panel is to consider Space Station *Freedom* as a long-term facility rather than a space mission. In other words, NASA should establish design, operating, and maintenance principles which minimize the disadvantages while fully exploiting the advantages of operating a long-term facility. This concept has a number of implications; the major ones are as follows:

  - Planning and operating a successful long-term facility requires an integrated optimization of such inter-related issues as component reliability, availability, maintainability, risk, life-cycle cost, schedule, spares and supplies logistics, staffing, and training. If this is not already in progress, NASA should promptly initiate the development of an integrated model incor porating these factors, and use it consistently across all Work Packages as a basic top-level planning and evaluation tool.

  - Regardless of the reliability of individual components, and even after feasible decreases in the component population, the Station will still need extensive replacements, refurbishments, and upgrades over its 30-year life. The operators of both industrial facilities and commercial and military aircraft fleets accomodate this situation by periodic maintenance outages or stand-downs, during which normal operations are curtailed and all available resources are concentrated on maintenance and upgrading. NASA should consider the applicability of this principle to the Space Station.

- The 30-year lifetime of *Freedom* will allow long-term monitoring of its performance. NASA should use the resulting information to create a solid R-A-M program combining performance tracking and trending, recurring failure identification, root cause analysis and closeout, and a reliability-centered maintenance and logistics program.

- The long lifetime of *Freedom* will also give its human operators time to accumulate profound expertise in its operational characteristics and eccentricities. Based on our experience with other long-term facilities comparable to the Space Station in complexity, experienced human operators can diagnose failures reliably from the information available from relatively simple instrumenation. Therefore, NASA should consider substituting the expertise of experienced facility operators for complex, expensive, and failure-prone monitoring and diagnostic instrumentation.

- This approach requires — and rewards — the creation of a cadre of experienced operators. For example, in the nuclear power industry, otherwise similar plants whose operators average more than five years' experience consistently perform better by all significant criteria than plants whose average operator experience is less than five years. NASA should thus minimize the turnover of the operators responsible for its major infrastructure systems, whether they are stationed in orbit or on the ground. (It may be advisable to create a permanent onboard crew position along the lines of a "chief facilities engineer").

Blue Ribbon Panel Report

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BLUE RIBBON PANEL

Panel Chairman: the Hon. Harrison H. Schmitt
Panel Rapporteur: Ms. Erin P. Collins, SAIC

Panel Members:

Mr. Anthony Feduccia, Rome Air Development Center (RADC)

Dr. Ronald L. Iman, Sandia National Laboratories

Dr. Harry F. Martz, Los Alamos National Laboratory

Mr. James Oberg, Space Flight Insight Services

Dr. Macgregor S. Reid, Jet Propulsion Laboratory

Dr. Jasper Welch, Jasper Welch Associates

Dr. Richard van Otterloo, KEMA, The Netherlands

12 June 1990

Mr. Joseph R. Fragola
Vice President and Operations Manager
Safety, Reliability, and Risk Analysis Operation
SAIC
342 Madison Avenue, Suite 1100
New York, NY 10173

Subject: Space Station *Freedom* EMTT Blue Ribbon Panel Final Report

Dear Mr. Fragola,

On behalf of the Blue Ribbon Panel, I have the pleasure to transmit to you the subject report. During our preparation and our three days of meetings, the Panel has been able to conduct a comprehensive review of the SAIC failure rate data analysis and methodology to assess the reasonableness and plausibility of the results. This report documents our findings and makes recommendations for your consideration.

Our objective and the focus of our discussions has been directed at the evaluation of the input information, the methodology, and the traceability of the analysis which SAIC used to develop and evaluate failure rate information for Space Station *Freedom*. Per your instructions the Panel did not consider it part of our mandate or scope to perform a detailed evaluation of the Space Station *Freedom* design and program. However, we have included additional recommendations which arose during the course of our discussions in areas related and allied to the focus of your study.

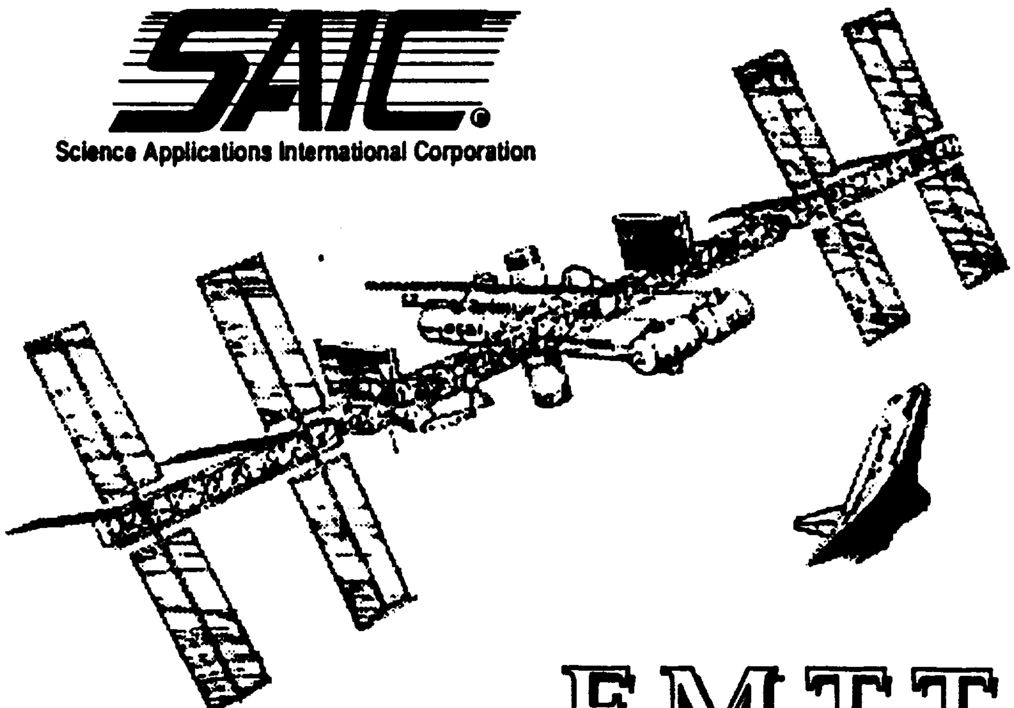
If I or the Panel can assist you or NASA in further endeavors of this kind, please do not hesitate to contact us.

Sincerely,

Harrison Schmitt /EPC

the Hon. Harrison H. Schmitt
Chairman

Science Applications International Corporation



EMTT

REPORT
of the
BLUE RIBBON PANEL
to review the
SAIC ANALYSIS OF FAILURE RATES

for the

SPACE STATION *FREEDOM*
EXTERNAL MAINTENANCE
TASK TEAM
(EMTT)

12 June 1990

MEETING BACKGROUND

Meeting Site: SAIC New York office
342 Madison Avenue, Suite 1100
New York, NY 10173

Meeting Dates: Wednesday, 6 June to Friday, 8 June 1990

Blue Ribbon Panel Chairman: the Hon. Harrison H. Schmitt

Panel Rapporteur: Ms. Erin P. Collins, SAIC

Panel Members:

Dr. Macgregor S. Reid, Jet Propulsion Laboratory
Dr. Ronald L. Iman, Sandia National Laboratories
Mr. James Oberg, Space Flight Insight Services
Dr. Harry F. Martz, Los Alamos National Laboratory
Dr. Jasper Welch, Jasper Welch Associates
Dr. Richard van Otterloo, KEMA, The Netherlands
Mr. Anthony Feduccia, Rome Air Development Center (RADC)

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SUMMARY

The Blue Ribbon Panel has evaluated the thoroughness of SAIC's methodology for Space Station Freedom (SSF) failure rate data analysis and, given the time constraints and limitations imposed on the analysis, has found it to be reasonable and technically sound. To establish internal consistency and reasonableness, SAIC performed appropriate checks on their assumptions with respect to other relevant programs. These checks showed the analytical results to be credible. The Panel also evaluated the SAIC assumptions and results relative to its own experience and found them to be consistent and plausible.

SAIC has also been diligent in maintaining the independence of its analysis relative to current NASA evaluations of related issues.

The Panel recommends that the thoroughness and robustness of the SAIC methodology be maintained and extended throughout the design, assembly, and operational phases of the SSF program.

The Blue Ribbon Panel agrees that the SSF should be considered as a facility rather than a mission. Examples of such considerations include the tradeoffs between redundancy and maintainability, the level of fault detection, and the operational margins included in facility services.

This report represents the unanimous judgment of the Panel.

1. FINDINGS

The Blue Ribbon Panel was provided a set of the presentation material which consisted of the latest available draft of the failure rate data analysis. This material was presented to the Panel via drafts of viewgraphs which, augmented with text, will constitute SAIC's final report to the Fisher-Price EMTT. Discussions were held with the SAIC analysts responsible for the work. Panel members had a first-hand opportunity to pose questions to SAIC on the analytical methods, assumptions, results, and the method of presentation of the analysis.

Following a full run-through of the latest results and SAIC presentation package, the Panel defined topics on which to focus their review and comments on the SAIC work. Feedback from SAIC was obtained as needed to ensure that the focus of the Panel discussion was centered on the technical issues of interest to SAIC.

Comments recorded during the discussions were reviewed by the Panel to reach a consensus on findings relative to the SAIC methodology and those related to the analytical results.

1.1 <u>Findings on the SAIC Methodology</u>

Given the boundary conditions and limitations of the study,

a. The three analytical methods comprising the SAIC methodology were performed independently, in a single-blind manner, and capture "top-down" and "bottom-up" approaches to the issue of SSF failure rate assessment.

b. The simulation method provides a realistic characterization of the month-to-month ORU failure profile projected over the 30 year SSF expected life. The ORU failure profile permits an examination of month-to-month variability and sensitivity to various parameters of interest.

c. SAIC has developed and applied both a standardized definition of ORUs across a wide scope of equipment types and program interfaces and a standardized data collection and validation procedure.

d. The analysis performed by SAIC is believed to be complete within the time, resources, and data available. Some limitations imposed on the analysis by virtue of these constraints and the study groundrules are discussed in Appendix A: Limitations of the Analysis.

1.2 Findings on the SAIC Analytical Results

a. The agreement among the results of the three independent, single-blind methods reinforces the credibility of the SAIC failure rate analysis.

b. The Panel examined factors that could both decrease and increase failure rates or the failure sequence. A list of such factors is included as Appendix A. While the precise effects of these factors are unknown, the Panel's review indicates that none would significantly affect the Panel's Summary Statement.

c. SAIC's in-depth review of the Work Package failure rate analyses enhanced the quality of the estimates now available at the Work Package level.

d. The Panel believes that the distribution of the number of monthly SSF ORU failures derived from SAIC's analysis is based on realistic assumptions and appropriate simulation. Table 1 represents one approach to summarizing the study results. The Panel recommends that such tables (or graphs) be included in SAIC's presentation to NASA.

e. The Panel recognizes that appropriate design modification and/or maintenance planning can significantly alter monthly ORU failure totals.

TABLE 1
SUMMARY OF EMPIRICAL RESULTS

Number of Monthly SSF ORU Failures	Estimated Frequency	Cumulative Frequency
8	2/360 = .0056	.0056
9	•	•
10	•	•
•	•	•
•	•	•
•	•	•
70	•	1.0000
	1.0000	

Mean = ________

Median = ________

2. RECOMMENDATIONS

Based on the SAIC presentations of analytical results, the Panel's background and experience on similar projects, their understanding of the technical and political environment surrounding this study, and expectations for the role to be fulfilled by SSF, the Blue Ribbon Panel compiled two sets of recommendations. The first set addresses overall recommendations on the study and the insights it provides to other SSF issues. The second set is directed to SAIC from the perspective of clarifying the analytical results and the presentation structure and content.

Appendix B presents some recommendations to NASA that were developed by the Panel.

2.1 Overall Recommendations

a. The Panel recommends that the methodology developed and employed by SAIC on this study be extended as applicable to future analytical needs.

b. The Panel recommneds that a comparably rigorous methodology and simulation model be maintained throughout the SSF design, assembly, and operational phases.

c. In view of the profound implications of SAIC's analysis, the Panel recommends that SAIC's results be reviewed with appropriate levels of NASA management before proceeding to the next phase in the SSF program. These results significantly impact the current details of SSF design, assembly plans, and operational procedures.

d. The Panel recommends that SAIC continue to emphasize that SSF is a facility, not a mission, from both a design and operational philosophy. Examples of such philosophical considerations include the tradeoffs between redundancy and maintainability, the level of fault detection, the operational margins included in facility services, and the impact of technological change.

e. The Panel recommends that SAIC suggest to NASA a review of SSF specifications for consistency with both the concept of a facility and the realistic consideration of the actual construction of that facility.

f. The Panel recommends that SAIC suggest to NASA that the additional steps needed to convert failure rates to EVA maintenance load be subjected to a comparably rigorous analytical review.

2.2 Recommendations to SAIC on Analysis and Presentation

a. The Panel recommends that SAIC try to obtain Spacelab information from Marshall Space Flight Center, bearing in mind that there are both pressurized and unpressurized data sets.

b. The Panel recommends that the issues of synergistic and cascade failures (dependent failures) be addressed in some manner.

c. The Panel recommends that the order of the performance of the three analytical approaches in relation to one another be noted in the presentation (e.g. in-service analysis conducted one week after synthesis analysis and Work Package data analysis performed two weeks after synthesis analysis). The difference between this order and the sequence in which the analyses will be discussed in the presentation should also be noted up front in the presentation package.

d. The Panel recommends that for those MTBFs in the Work Package data table that are greater than 100 years, the notation "Greater than 100 years" be used rather than the number. In addition, units should be added to the headings for each column.

e. The Panel recommends that SAIC not include the Hubble Space Telescope failure data estimates in the overall combined estimates by device type (electrical, electronics, etc.) since the population of Hubble ORUs is substantively smaller than the postulated ORU population for other device type combined estimates.

f. The Panel recommends that SAIC re-examine the mechanical device type synthesis estimate to verify the results and the uncertainty bounds.

g. The Panel recommends that the Random Failure Analogy summary be revised to include the latest available spacecraft in-service data from the Voyager, Skylab, Space Shuttle, Mir/Salyut, and Goddard experience, and that it be presented in top-down order from lowest number of failures per year to highest.

h. The Panel recommends that SAIC place a line at 1.4E-03 failures/hour on the chart summarizing the in-service estimate data to show where the SSF design goal lies.

i. The Panel, stressing the importance of the list of "big hitters" (top contributors), recommends that SAIC analyze this list further to evaluate uncertainty/sensitivity issues in the data.

j. The Panel recommends that SAIC provide some bound on the uncertainty in the definition of ORUs in the Work Package data.

k. The Panel recommends the inclusion of introductory viewgraphs (as per J. Welch's ideas) to set the stage for the presentation.

l. The Panel recommends that SAIC specify clearly at the beginning of their presentation that their study was confined to the 1/1/90 SSF design.

m. The Panel recommends that SAIC consider addressing the tentative nature of the Work Package data by citing the number of man-months it would conventionally take to develop MTBF data.

n. The Panel recommends that SAIC note that the present life-limit analysis is based on a set of "artifacts" that could call the rest of the analysis into question, namely:

(a) Selection of round numbers for estimates of life-limit
(b) Assumption of a fairly small sigma on the life-limits
(c) Assumption that all equipment is assembled at the same time
(d) Assumption that duty cycle is the same for all components of the same type

o. The Panel recommends that SAIC attempt to quantify the potential degree of influence on the data analysis of the issues listed on the Appendix A list.

p. It is a recommendation of the Panel that SAIC address the need to qualify the data at the ORU level, not just at the SSF level, via comparisons between Work Package data and other appropriate systems (such as the Hubble Space Telescope data).

q. The Panel recommends that SAIC statistically summarize the 360 peaks of the ORU failures per month curves so that the frequency of having a certain number of failures per month can be evaluated [see Table 1].

r. The Panel recommends that SAIC show limited life items separately in one example of the ORU failures per month bar chart.

s. It is a recommendation of the Panel that SAIC consider defining all equipment terms such as ORU, LRU, device, module, etc. in relation to one another to avoid confusion in their use.

t. The Panel recommends that SAIC consider the operational environment of spacecraft in comparing their failure data. For example, the operational environment of the Voyager 2 spacecraft is significantly different from that of many Goddard Space Flight Center missions.

u. The Panel recommends the use of the x-y plot conceived by H. Martz to show what is needed to achieve various numbers of EVA/month.

v. The Panel recommends that SAIC note the amount of designed-in redundancyin the SSF and its impact on the Work Package equipment failure data.

w. The Panel recommends that SAIC construct a slide that shows the range of duty cycle estimates (low, present analysis, "real world") for use in the presentation to NASA. In particular, it was recommended that the duty cycle be increased by 50% for those components not already at 1.00.

x. The Panel recommends that SAIC note that potential ORU failures are distributed over a limited number of ORU types. Life limit failures contribute significantly but do not dominate the overall failure rate, except in the 20 ORU types that produce 50% of the total failures.

y. The Panel recommends that SAIC perform a verification and validation on the simulation code and the code results.

APPENDIX A
Limitations of the SAIC Failure Rate Analysis

EFFECT	UNCERTAINTY IN FAILURE RATE DATA MAY EXIST DUE TO:
+	Common Mode failures (design flaws)
+	Common Cause failures (external event caused)
+	Dependent failures cascade; one failure causes another)
+	Maintenance/Operations-induced failures (Examples: robot or human-induced; any damage in inventory; chemical/temperature contamination; shuttle plume)
+-	Design immaturity of ORU
+-	Data and analysis immaturity
-	Reliability improvement program(s) (near-term); include FMECA*
-	Advances in Technology (long-term)*
-	Installation (Assembly) sequence and impact on early failure rate and resulting maintenance and sparing
#	Limitations of Life-Limit Model
+	Duty Cycle
+-	Definition of "ORU"
+	Operational immaturity / experience (may not initially use equipment in an optimal way)
+-	Configuration immaturity of SSF (current design, no experimental payload considerations)
+	Construction-induced failures*
+	Unrecognized and underestimated stresses on SSF and/or ORUs
+-	Unknown- unknowns

+ = increases failure rate

- = decreases failure rate

= affects timing of failure

* = items that could have more significant impact than the others

BLUE RIBBON PANEL

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APPENDIX B
Items for NASA Consideration

As a primary conclusion of its discussions, the Blue Ribbon Panel recommends that NASA adopt a systematic analysis approach (such as FMECA) as a means for addressing the issues raised by SAIC's analytical results. Based on the Panel's collective experience on other programs, it is believed that such analyses could lead to significant improvements in design, assembly, logistics, and on-going operation. It is also believed that such analyses would lead to short- and long-term options for improvement.

Some, but not all, considerations raised during the Panel's deliberations are given below:

a. The Panel recommends that NASA consider instituting an Inspection & Maintenance protocol for items that degrade over time as a means for reducing Failure Rate.

b. The Panel recommends that NASA address potential failures due to Software-induced damage.

c. It is a recommendation of the Panel that NASA investigate Shuttle plume effects (especially for solar panels).

d. It is a recommendation of the Panel that NASA evaluate EVA efficiency (e.g., suit design and maintenance scheduling).

e. The Panel recommends to NASA that when possible, maintenance should be scheduled to occur concurrently with the arrival of shuttle crews with particular expertise or crew size.

f. The Panel recommends that NASA thoroughly establish the criticality (consequence) of replacing different ORUs and an algorithm for prioritizing repair.

g. It is the consensus of the Panel that the number of MDMs and other redundant ORUs impacts adversely on the volume of maintenance. The Panel also believes that it may be possible to address this issue without significantly impacting the entire SSF design.

h. The Panel recommends that after the SSF failures and failure modes are identified and logged (via a system such as PRACA), a means for closing-out failures and prioritizing the close-outs be utilized.

i. The Panel recommends the development and implementation of a "Living" systems engineering model to evaluate global tradeoffs (such as logistics to orbit and configuration choices) and "fixes" as needed.

j. The Panel recommends that NASA make a concerted effort to reconstruct the failure history of prior and current programs.

k. The Panel recommends that NASA consider the impacts on SSF equipment and structures (such as airlocks) of factors of "x" increase in the number of maintenance EVAs.

l. The Panel recommends that if NASA intends the SSF to have an indefinite life, a preventive maintenance program will need to be in place that addresses scheduling of maintenance actions related to the fundamental infrastructure of the SSF.

m. The Panel recommends that NASA recognize that only the base SSF equipment is addressed in the present failure rate and EVA analyses. The ORU failure rates for experimental payloads, etc., which may also have a significant impact on total repair load, are not addressed.

n. It is a recommendation of the Panel that NASA consider the pros and cons of an SSF construction Quality Assurance program.

o. The Panel recommends that NASA recognize that a Maintenance Significant Item is not equivalent to an ORU and that the ratio between the two needs to be determined to evaluate SSF maintenance requirements.

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